Solar, wind and logistic substitution in global energy supply to 2050 – barriers and implications

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Abstract

The sustained rapid growth and learning rates displayed by solar PV and wind electricity generation capacity over recent decades appear to be unprecedented. With these technologies now available at costs competitive with - or below - those of fossil fuel incumbents in many parts of the world, high rates of growth appear likely to continue. In this paper we use 'top-down' _extrapolation of global trends and simple and transparent models to attempt to falsify the proposition that PV and wind have the potential to achieve dominance in global primary energy supply by 2050. We project future deployment of PV and wind using a logistic substitution model, and examine a series of potentially fundamental constraints that could inhibit continued growth. Adopting conservative assumptions, we find no insuperable constraints across physical and raw materials requirements, manufacturing capacity, energy balance (EROEI), system integration and macro-economic conditions, to this outcome. We also demonstrate synergy with direct air carbon capture and storage (DACCS) that would allow the achievement of global net-zero CO2 emissions by mid-century. Achieving such an outcome would require large scale reconfiguration of the architecture of global and regional energy systems, particularly from 2040 onwards. Low cost primary electricity is likely to be a significant factor in driving such a reorganisation. But given the speed and depth of the transition, hurdles will remain that will require foresight and strategic, coordinated action to overcome.

Highlights

- Extrapolating PV and wind deployment using logistic substitution suggests they may dominate global energy supply by 2050.
- There are synergies between PV and wind, and DACCS. DACCS adds flexibility to a renewably powered energy system.
- This supply-side transformation would both drive and require a wholesale reconfiguration of the rest of the energy system.
- With DACCS, this process could reduce net global CO2 emissions from energy to zero by 2050, and below zero thereafter.
- There appear to be no insuperable physical or economic barriers to such an outcome.

Keywords: Energy Transition; Logistic substitution; Solar PV; Onshore Wind; Offshore Wind; Physical constraints; Economic constraints

Word Count: 9,010

Abbreviations

AGR	Annual Growth Rate
BECCS	Bioenergy with Carbon Capture and Sequestration

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C-Si	Crystalline Silicon
CdTe	Cadmium Telluride
CAGR	Compound Annual Growth Rate
CIS	Copper Indium Selenide
DACCS	Direct Air Carbon Capture and Sequestration
EROEI	Energy Return On Energy Invested
GCM	Global Climate Models
GWP	Gross World Product
HVDC	High Voltage Direct Current
IAM	Integrated Assessment Models
LCOE	Levelised Cost of Energy
LCOS	Levelised Cost of Storage
LCOT	Levelised Cost of Transmission
SOLWIN	Solar PV and Wind
SSP	Shared Socio-economic Pathways
TPES	Total Primary Energy Supply
WACC	Weighted-Average Cost of Capital

1. Introduction

The rapid increase of global solar photovoltaic (PV) and wind power capacity in recent decades has been striking. The annual growth rate for installed (onshore and offshore) wind capacity between 1980-2018 averaged 25% [1,2], and 35% for solar PV over the period 1996-2019 [2,3]. This compares with the average annual growth rate for global primary energy supply and consumption (TPES) over the period from 1990-2019 of just 1.87% [4].

Such large, and relatively consistent growth rates appear to be historically unprecedented for any energy supply technology. For comparison, coal consumption in England & Wales is thought to have grown by around 3.5% per annum in the first half of the 19th Century[†] [5], and global oil consumption by just over 7% per annum over the period 1890-1920, during which each fuel accounted for between 1% and 10% of global primary energy consumption [6].

In absolute terms, PV and wind together currently account for a little over 1% of global primary energy supply (TPES). The most recent annual increment of PV and wind represents about one quarter of 1% of TPES. The impact of PV and wind on the global energy mix, to date, is therefore negligible. But what this observation overlooks is that the annual percentage rate of growth of these two technologies is more than an order of magnitude higher than the annual percentage rate of growth of global TPES, and much higher than the growth rate of hydropower.

A growth rate of 25% in global PV and wind generation would, if continued, lead to a roughly 10-fold increase within a decade. Within 11 years, it would see the annual increase in global solar and wind exceed the whole annual increment in TPES. At this point, global PV and wind, while supplying just 10% of global TPES, would have reduced the aggregate annual increment of more conventional forms of energy to approximately zero. If continued for a further 12 years, global PV and wind would account for the whole of global TPES. While perhaps surprising, these results flow directly from the properties of exponential functions, including the fact that, regardless of where either begins, a faster exponential function inevitably overtakes one slower.

[†] The quality of the data prevent a definitive conclusion.

While highly simplified, the above extrapolation of recent trends suggests that the world is on the brink of a transition from a global energy system based predominantly on fossil fuels to one based on renewable energy. There is a large literature on the possibility of such a transition. Jevons, writing in 1865, provides one of the earliest references to the possibility of replacing coal with hydrogen [5]. In a seminal work, Sørensen, focusing purely on Denmark, established the technical feasibility of a transition to a mix of solar PV and wind by 2050 [7]. Several more recent contributions have been made (e.g. [8–14]). Among these, some focus on the end state, but do not treat the transition in depth [8,9]. Some focus on electricity, but not on the whole energy system [15,16]. Some lack detail and insights from more recent literature on physical and economic constraints [10,11],[12,13]. Some adopt a normative approach, taking the necessity of achieving early climate goals as their starting point [14,17].

The rate at which PV and wind displace primary fossil energy from the global energy system depends on four key factors. The first is the proportion of TPES currently used to generate electricity, which - *ceteris paribus* - may be directly substituted. At the time of writing, this sits at around 27% of global TPES (over 70% of which is from fossil fuels), with electricity satisfying around 20% of final energy demand [18]. The second factor is the extent to, and rate at which final energy demand may be electrified, or be satisfied by secondary forms of energy that may be produced using electricity. The third factor is the supporting infrastructure required to balance supply and demand, when supply is dominated by variable PV and wind. The fourth factor is the change in end-to-end efficiency of the energy system, and thus the ratio between primary energy supply and final energy demand [14,15,17].

The work described here therefore follows the following steps:

- we project global primary energy supply assuming a continuation of recent growth trends, and including, from 2040, energy required by a programme of DACCS (Section 2);
- assuming that PV and wind can displace all fossil energy from the global energy system, we project global PV and wind generation to 2070 using a logistic substitution model with an assumed 100% asymptotic substitution level (Section 2);
- For projected increments of capacity in 2050, we estimate the physical requirements for PV and wind deployment, and associated downstream energy conversion and transport infrastructure, and compare these against relevant constraints - land and sea areas required for deployment and potential for climate impacts (Section 3), demand for raw materials (Section 4), the dynamics concerning Energy Return on Energy Invested (EROEI) (Section 5), the availability of manufacturing capacity (Section 6), and requirements for energy system integration (Section 7);
- We estimate the investment requirements for PV and wind deployment and review potential economic constraints for such growth in PV and wind, alongside key integrating technologies (specifically batteries and transmission infrastructure), focusing on global energy supply investment requirements, and the 'Bashmakov-Newbery constant' of total expenditure on energy consumption [19] (Section 8).
- Where requirements of PV and wind approach or exceed any of the above constraints, we briefly review means by which they might be circumvented.
- Finally, we review potential synergies between PV and wind deployment and Direct Air Carbon Capture and Sequestration (DACCS) and implications for global CO_2 emissions (Section 9),
- Section 10 concludes the paper.

In summary, we use 'top-down' extrapolation of global trends, and simple and transparent models, to attempt to falsify the proposition that PV and wind have the potential to achieve dominance in global primary energy supply by the middle of the 21st Century.

A key question in any exercise aimed at extrapolating from historic data surrounds the dynamics of process and of appropriate functional forms. We will argue that the question of functional form is not one that can be deduced from historic data, particularly at an early stage in an energy transition. On the contrary, one has to take a theoretically and historically informed position on the likely shape of such a transition. On this question, the authors have been heavily influenced by the work of Marchetti and Nakicenovic [6], who in turn built on a literature on technology substitution exemplified by Fisher & Pry [20]. Following Marchetti and Nakicenovic, we will henceforth refer to the combination of solar PV and wind as SOLWIN.

2. Projections of global energy demand and of PV and wind energy generation

We begin this section with a brief examination of some of the problems with such projections through the lens of two recent papers. Hansen et al. [21] examined historic data to 2016, and noted that annual growth rates for SOLWIN capacity and generation have been below the long-term average since the early to mid-2010s. They considered this downturn to be significant, and that a logistic function yielded a better fit to the historic data than an exponential. Extrapolating using a fitted logistic curve, they find installed capacity saturating by 2030 at a level just 50% higher than installed capacity in 2019. The main problem with this conclusion is that Hansen et al. did not propose a mechanism that could plausibly result in saturation at this level. In the absence of a well-defined mechanism, there is a risk of assuming that socio-political and technical mechanisms that have driven variations in deployment rates over the last 25 years, and particularly since 2015, would continue to operate though the coming 30. This seems unreasonable, given that annual generation from SOLWIN has increased by almost 2 orders of magnitude over this period, moving from niche applications such as satellites and pocket calculators in the 1970s, and from countries where these technologies were heavily subsidised [22], decisively into unsubsidised, utility-scale applications in multiple countries only since 2016.

Rypdal, using an alternative approach, found no grounds based on historic data to reject the hypothesis of exponential growth in favour of a logistic model, with the recent decline consistent with noise in a long-term trend [23]. The present authors are likewise unpersuaded that statistical analysis of empirical deployment data for penetrations in the range of 0-1% of the potential market can reliably distinguish between exponential and logistic substitution processes, since exponential and logistic functions differ by less than 1% in this range, and real-world noise (e.g. discontinuities in policy support for renewables in the handful of countries that have provided significant support for early deployment) will almost certainly exceed this.

However, the same logic also precludes the possibility of reliably determining ultimate saturation levels for logistics from historical data – since in this range of penetration and in the presence of noise, an exponential function is indistinguishable from a logistic with an infinite saturation level. Fundamentally, historic deployment and contextual data do not contain sufficient information about future conditions to enable any reliable inter-decadal projection of future growth rates or saturation levels of PV and wind energy within the global energy market.

There are however, theoretical grounds for preferring a logistic model. The argument is as follows. Empirically, technology substitution trajectories tend to approximate to exponential for the first half of such transitions, but depart from this thereafter. Factors that tend to lead to early exponential growth include economies of scale and learning. As deployment has grown, the levelised cost of energy (LCOE) from solar PV and wind technologies has fallen precipitously, particularly over the last decade, with utility-scale solar and onshore wind now representing the cheapest source of new power generation for two-thirds of the global population [24]. The interaction between deployment and cost reduction constitutes a feedback loop, providing a foundation upon which, in the absence of constraints, growth rates approximating an exponential trajectory may continue. As noted above, it is straightforward to show that if exponential growth were to continue unimpeded at rates seen over the last 5 years, SOLWIN generation would cap growth of all other sources of global primary energy supply as early as 2030[‡], and would displace all of global primary fossil energy supply before 2050.

However, there are, in the real world, almost always constraints on growth. Multiple mechanisms, including the likelihood that the last tranches of the incumbent technology to be displaced will have the lowest costs of production and will be concentrated in niche applications, and recognition by all stakeholders (including system manufacturers, installers, governments and financiers) of the implications of approaching market saturation for further investment, lead to progressively slower growth rates, sigmoid growth curves and asymptotic approach to saturation. The phenomenology across the whole of any transition can be formalised through variants of the logistic function, the classic application of which in the energy field is by Marchetti & Nakicenovic [6]. The alternative of an exponential trajectory would result, at the point of market saturation, in a circa two order of magnitude reduction in demand, as the SOLWIN supply chain switched from building c.25 TW of new capacity per year, to replacing c.0.2 TW of plant that had been installed some 30 years earlier. The impact of such an abrupt change in activity on the global economy would likely be problematic.

Having set out the basis for our approach, we now present a set of projections of global energy demand and supply, from 2019-2070. Figure 1 illustrates four main projections, for this period. First, we project global TPES to increase at 1.87% per year; the average rate of growth between 1990 and 2019 [4], comparable to quantifications of the 'baseline' scenario (i.e. no temperature or emission constraints) for Shared Socioeconomic Pathway 2 (SSP2), reflecting 'middle of the road' developments compared the other four SSP narratives [25]. From 2040, the deployment of DACCS is assumed to lead to an additional category of primary energy demand characterised by a negative carbon dioxide intensity (see Section 9).

[‡] The capping of growth of fossil fuels takes place when the annual increment of PV and wind generation equals the annual increment of total primary energy demand. Since the historical and assumed future growth rates of PV and wind exceed, by several times, the projected growth rate of total primary energy demand, this occurs well before saturation.

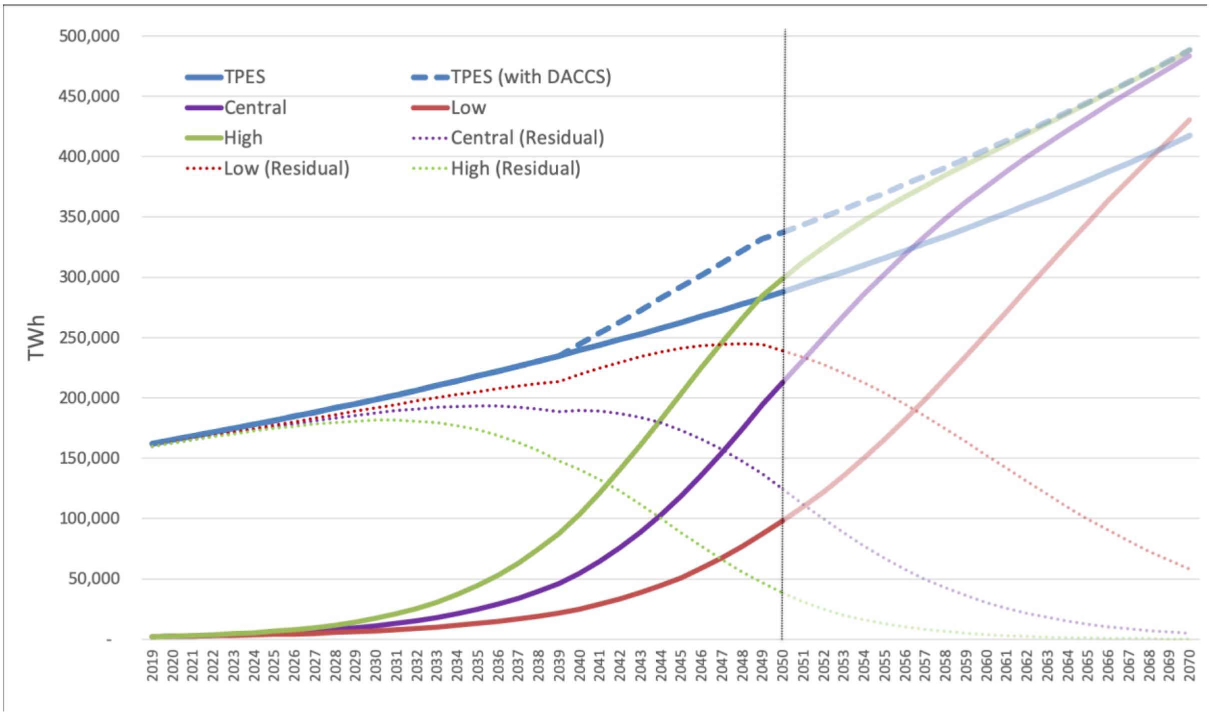

Figure 1 - Projections for TPES, SOLWIN and Residuals

The second projection ('Central') is the sum of TPES provided by solar PV, offshore and onshore wind under separate logistic trajectories. For calculation purposes, we use a discrete form of the two-factor logistic equation described by Fisher & Pry [20]. For this calculation we adopt initial incremental growth coefficients for generation from each individual technology, set at 20% for solar PV and offshore wind, and 10% for onshore wind. Further details of the logistic projection calculation are set out in the Appendix to this paper.

The third and fourth ('High' and Low') projections are sensitivities around the Central projection, with growth coefficients for each technology set at 5 percentage points higher and lower, respectively. The resulting growth rates bracket observed annual rates growth for all three technologies over the period 2000-2018. Tabulated generation and associated capacity values for all three logistic projections are presented in Table A1, in the Appendix. 'Residual' trends are simply the remaining primary energy supply not provided by SOLWIN (which from 2040 is inclusive of energy demand for DACCS).

In the following sections we review various physical and economic factors to determine, using high-level principles and simple numerical models, whether or not they represent fundamental constraints to the continuation of recent trends by 2050. Although we extend our projections in Figure 1 and Figure 2 below to 2070, primarily to illustrate implications of CO_2 emissions from the energy sector for 2 and 1.5°C climate targets, we analyse constraints to 2050 only, as this is the benchmark year against which trends, commitments and impacts in energy system transitions are most often compared, and beyond this, complications such as increasing rates of SOLWIN capital stock replacement and raw material recycling begin to become more significant, and start to cloud assessment of the high level principles we seek to examine. We focus most of our analysis on the Central projection, which approximately continues recent trends. We also restrict ourselves to a high level discussion of dynamics at the global level, with detailed discussion of regional, sectoral and technical specificities being beyond our scope.

3. Land, Sea and Climate

We first test SOLWIN deployment against the fraction of global land and/or sea area that would need to be occupied[§] by SOLWIN installations. For simplicity, we explore the impacts of PV, and onshore and offshore wind deployments of 95.8, 18.5 and 6.4 TW (peak) respectively, representing deployments seen in the High trajectory for 2050. With the assumptions set out in the Appendix, the resulting areas occupied by the three technologies would be 0.96, 18.5 and 6.4 million km^2, equivalent to 0.6% and 12.5% of global land area, and 1.8% of global sea area respectively. Although the areas of land and sea spanned by wind are large, the assumed density is the equivalent of roughly one 10 MW(rated) wind turbine per 10 km^2. At this density, wind power would be compatible with most other land and sea uses. The areas themselves appear manageable.

The second test is whether such deployments might have the capacity to directly change global or regional climates, in addition to their role in CO_2 mitigation. In principle, by reducing the albedo of the surface of the earth, PV contributes to climate forcing. Estimates of regional impacts of large-scale wind deployment have been made using Regional Circulation Models [26], but we are unaware of any modelling of such impacts using Global Climate Models (GCMs) for wind or solar PV.

It is straightforward to estimate first order radiative effects of PV, based on likely differences in albedo between PV arrays and the natural surfaces that they are deployed upon. The increase in CO_2 concentration from 280 ppm to 415 ppm over 1750-2019, represents an additional radiative forcing of c.2.1 W/m^2. Without significant action to decarbonise the global energy system, atmospheric CO_2 concentration would likely rise to around 500 ppm [27,28], and climate forcing to approximately 3.1 W/m^2 by 2050. At this level, the first order forcing from 96 TW of PV could be offset by reducing the mid-century CO_2 concentration by less than 5 ppm, representing less than 2 years of unconstrained growth in atmospheric CO_2 at mid-century[**]. From this perspective, the effect of growth in PV through to mid-century would appear to be manageable.

As suggested above, climate impacts of wind are more complex. Here we simply compare projected annual global wind generation of c.25 TW in 2050 to an estimate of the available energy in the global wind system, estimated by Lorenz [29] at 4 PW[††]. The former is c.0.25% of the latter. Again, we conclude that this is probably manageable, but if the future were to show otherwise, for example because of the emergence of regional scale effects, impacts could be mitigated by rebalancing the mix of PV and wind.

4. Raw Materials

The potential for raw material availability to constrain growth in renewables has received reasonable attention in the literature, e.g.[30–32]. In this section we explore requirements for a range of 29 metals used across the lifecycle of solar PV and wind installations, for deployment to 2050. We also explore metal requirements needed to support the deployment of sufficient battery storage to facilitate the integration of the projected levels of SOLWIN, as discussed further in Section 6, below.

[§] A PV installation physically covers most of the land or sea areas it occupies. In contrast, a wind array physically covers a small fraction of the area it occupies. The reader therefore may wish to think of wind arrays as "spanning" areas of land or sea. But the verb "occupy" is a convenient shorthand when talking about both technologies.

[**] It has been put to us that it is obvious that PV would have negligible impact on climate. Our response is that since a first order estimate is relatively simple to make, we would prefer to make it. The impact does indeed turn out to be small.

[††] We choose this particular estimate, because it is based on a thermodynamic analysis of the atmosphere.

We use the lifecycle data for C-Si, CdTe and CIS PV systems (3kW), 2MW offshore and 800kW onshore wind installations, and NCM811 batteries (assuming an energy density of 300 kWh/kg) along with associated global resource, reserve and annual production data for 2018 provided by Moreau, Reis & Vuille [30], supplemented by data for global resources for tin [33].

First, we assume annual production (and thus consumption) for all metals, for all current purposes (as given by Moreau, Reis & Vuille, 2019 [30]), remains constant between 2018 and 2050. For some metals, this alone exhausts current reserves (see Tables A2-A4, in the Appendix). We assume that metal demand for all SOLWIN and battery deployment for 2020-2050 is fully additional to current production (although some production would be to satisfy current demand for these technologies, it would be relatively minor).

For the purposes of our calculations, we also assume that: (a) for solar PV deployment, C-Si accounts for 90% of annual deployment (compared to around 95%, currently [34]), with Cd-Te and CIS accounting for 5% each; (b) replacement of aging SOLWIN capacity stock is not considered (although stock replacement would start to become significant toward mid-century, it would likely remain small compared to total installation until well into the second half of the century); (c) but, given the relatively short lifetime of batteries (see Section 6), metal demand for battery capacity replacement *is* considered, (d) lifecycle metal requirements (per kWh) remain constant over time, for each technology; (e) no metal recycling occurs; and (f) there are no new additions to resources, and no reclassification of resources to reserves. Taken together, these factors lead to what are likely to be conservative (over-)estimates of metal demand. The full results of the calculation for the three pathways are presented in Tables A2-A4, in the Appendix.

We estimate that by 2050 demand for cadmium, gold, lead, silver tin and zinc for other purposes will exceed reserves if current rates of production are maintained. Even excluding demand for other purposes, demand for cadmium for the production of PV systems may exceed global reserves under the Central projection, and exceed the known global resource under the High projection. Material requirements for wind installations place additional pressure on nickel, increasing potential demand to just 84% of known resources in the High trajectory (but negligible impact on almost all other materials examined). Studies have examined whether demand for key materials may lead to extraction rates that exceed historic levels [27,35] , but we find no evidence of fundamental limits to such rates.

Historically, a key factor in delaying or avoiding materials constraints on the global economy has been the human ability to innovate to avoid them, through a combination of discovering more of the resource, improved material efficiency, or substitution [36]. In the case of PV, previous studies conclude that cadmium and silver intensities of CdTe and C-Si panels (respectively) could reduce by 90% by 2030 and 2050 (respectively)[35,37], or in the case of silver, be substituted away entirely if prices were to rise even modestly [30]. The development and use of alternative materials and technologies, from near-term options such as perovskites, and those more distant, such as quantum dot cells [38], could further reduce resource impact. Material recycling would likely become important in the long-term, to help satisfy ongoing demand, but would have a negligible impact before 2050 due to the rate of deployment and expected lifetime of installations.

The deployment of battery storage will place further pressure on key resources and reserves, potentially requiring up to 2.5 times global resources of nickel even in the Low projection (rising to 7.8 times in the High projection), and double that of lithium under the Central trajectory (or 0.9 and 2.8 times, respectively, under the Low and High projections), by 2050. Although uncertainty necessarily remains, innovation would also be expected to substantially reduce eventual demand for these metals through increasing efficiencies, or the adoption of alternative battery chemistries [39] or storage technologies (e.g. molten salt storage) [40].

5. Energy Return on Energy Invested

There is a rich literature on the energy balance of renewable energy technologies. Our analysis is based on a small sample of this [16,41–43]. A simple criterion for an expanding programme of deployment of any energy technology to break even is that:

$$\frac{capacity_{i+1}}{capacity_i} < EROEI/N$$

where $EROEI$ is the energy return on energy invested, and N is the expected operational life (in years) of each successive tranche of the technology. If one assumes $N = 30$, and a maximum fractional annual increment of 0.25, then it is easily shown that the limiting value of $EROEI$ is:

$$EROEI_{limit} \approx 7.5$$

EROEI values reported for wind are consistently above 15, similar to estimates for nuclear [44], and are therefore a factor of 2 above this limit.

For PV, estimates for EROEI of below 2 have been reported by Ferroni & Hopkirk [45], however a review of this study by Raugei et al. [41] identifies methodological and data issues and suggests that more realistic range of EROEI for systems sited in Switzerland (46-47.5°N) would 9.1-9.7. Deployment at lower latitudes would lead to EROEI values 50-80% higher, due simply to increased solar irradiance. Since we expect future global deployment of PV to be dominated by systems at lower latitudes, we feel confident in predicting global mean EROEI for future PV installations to be at least 15, even without recent and potential future improvements in PV and PV manufacturing technology. More generally, rapid growth and high learning rates for both PV and wind mean that that estimates of costs in the literature will tend to be higher, and estimates of EROEI lower than for systems currently being commissioned, and that economic and energy costs, will continue to fall in the future.

Finally, we note that for a logistic trajectory, the fractional annual increment falls progressively from the initial values presented at the beginning of this paper, and is halved by the time a penetration of 50% is achieved. We conclude that, with the assumptions set out at the start of this paper, EROEI is unlikely to constitute a significant constraint on deployment of PV and wind over the coming century.

6. Manufacturing capacity

To satisfy demand, manufacturing capacity for solar PV and wind components and installations would have to grow at roughly the same pace as annual deployment. We see no fundamental reason why this could not be achieved under any of our projections. For solar PV, since the mid-2000s manufacturing capacity (particularly in China) grew at a faster rate than production, leading to overcapacity, price competition and subsequent market consolidation (with utilisation rates for PV module manufacturing capacity fluctuating between 61-74% since 2010 [46]). Despite this, two-thirds of current manufacturing capacity for C-Si cells was commissioned after 2015 [47]. Additional capacity announcements have continued, with 212 GW-worth of new manufacturing capacity for C-Si cells and 123 GW for silicon ingot/wafer production, announced in first four months of 2020 alone – more than the expansion announcements made in all of 2019, for both manufacturing stages (and four times that for C-Si cells) [48]. Technical developments will likely facilitate further manufacturing capacity expansion. Silicon wafers for C-Si units may be thinned, for example, reducing expansion requirements for the ingot/wafer production stage (and overall costs) [49].

Manufacturing limits for wind currently centre around tower and blade production capacity [50,51] but with growth continuing to be delivered in large part through increasing individual unit capacity with larger towers and turbines (ratings of onshore turbines are set to double to around 5 MW by 2025, and offshore turbines to reach 20 MW within 10-20 years [52]) the number of units, and the number and size of manufacturing plants required, will increase at a rate lower than capacity growth.

Over time, decreasing returns on investment as deployment approaches saturation would slow growth in manufacturing capacity, with demand for new installations ultimately constrained by the rate of energy demand growth, and the need to replace aging installations. However, as the former decreases, the latter will increase. This will go some way to providing a long-term 'soft landing' for SOLWIN supply chains.

7. Energy & electricity demand, and system integration

It is clear that substantial proportions of currently non-electric final energy demand satisfied by other (largely fossil) fuels may be electrified – particularly space and water heating in buildings, light road passenger and freight transport [53] and short-haul aviation [47,54] which are collectively responsible for over 30% of global final energy demand [18]. For other end-uses, such as long-distance road, air and sea transport, fuels derived from electricity – in particular hydrogen – are likely to be more appropriate. The conversion of shipping and long-haul road freight, and of all petrochemicals, to hydrogen would be technically and chemically straightforward. Use of hydrogen in cement production is also being actively trialled [55]. Petrochemicals and probably long-haul aviation will continue to require hydrocarbons. We assume that these will ultimately be derived from hydrogen. Ammonia, which can be straightforwardly derived from hydrogen, is under consideration for shipping [56].

Across the economy, ongoing innovation is likely to progressively extend the scope of electrification, for example, in the case of heat in industry (responsible for around 21% of current global final energy demand [18]). Process heat at temperatures up to 200°C that cannot be provided by cascading waste heat from higher temperature processes, can in principle be provided by heat pumps. Electric heat pumps with output temperatures of up to 150°C are already available [57], and systems with output temperatures up to 200°C are deemed feasible [58]. Cascading requires integration of processes and energy flows and is supported by technologies such as District Heating and Cooling (DHC) [59]. Heat at yet higher temperatures can be provided either by hydrogen or hydrogen-derived fuels, or by direct electric heating. Use of hydrogen in iron smelting, both as a source of heat and as a reducing agent, is being actively examined [60].

In the long-run, we consider it reasonable to assume that nearly all global final energy demand may be satisfied either directly by electricity, or by electricity-derived fuels (particularly hydrogen and its derivatives). Although the market share of SOLWIN in global primary energy demand does not reach the current level of primary consumption used to generate electricity until around 2040 in the Central projection, preparations for a demand-side transition must begin now for it to be sufficiently advanced to facilitate continued growth of SOLWIN as we approach mid-century. Although there are encouraging signs that such demand-side developments are accelerating (e.g. with electric cars rapidly increasing their market share in key markets [61]), the multiple, complex interactions, lead-times and uncertainties that surround demand-side dynamics are among the several reasons that SOLWIN deployment is likely to follow a logistic trend.

A global energy system dominated by SOLWIN in energy supply, and by electricity (or derived products) in energy demand, may take innumerable specific configurations, with highly varied contributions from specific technologies and mechanisms to connect and mediate between supply and demand. In this paper, we focus on two technologies that are commonly cited as key components of such a system – High Voltage Direct Current (HVDC) transmission lines, and battery electric storage. With the exception of raw material requirements for batteries (see Section 4), we restrict our analysis of these technologies to the economic requirements and implications of the deployment of sufficient HVDC and battery capacity to transmit, store and discharge 50% of global generation by 2050 (see Section 8).

The topology of the energy system, and the nature of individual sub-systems from generation to transmission, conversion to other energy products, storage, and use, would likely alter substantially with high levels of SOLWIN. The overall effect would be a transformation of the system architecture[‡‡]. There are multiple historical precedents for the re-shaping of the energy system in this way, under pressure of supply-side transformations [62].

End-use electrification [14,15,17] and adaptations to the availability of electrolytic hydrogen would likely bring efficiency improvements in their wake. Around 39% of the primary energy currently entering the global system is lost before it reaches the end user [18]. Electrification tends both to reduce the number of intermediate energy conversion steps required, and thus losses incurred, between primary and final energy consumption, and supports more efficient end-use technologies, such as heat pumps and electric motors (for which each Joule of renewable electricity can displace between 3 and 4 times as much fossil primary energy [63]). However, electrification introduces other categories of loss. In addition to local electricity transmission and distribution infrastructure already in use (with losses of around 10%), long-distance HVDC transmission and batteries used to provide secure and reliable supply [64] would also introduce losses, but which would be unlikely to exceed 20% (see Appendix). Losses associated with the electrolytic production of hydrogen are of the order 25% [65], though in principle, overall efficiency of hydrogen energy conversion chains can be increased by the use of exergy-efficient end-use systems such as fuel cells.

On aggregate, on the basis of a simple sectoral analysis we estimate the ratio of SOLWIN generation to conventional primary fossil fuel energy displaced to be approximately 0.7:1, and judge that it is unlikely to exceed unity (see Table A5, in the Appendix). Our assumption of a 1:1 ratio is therefore likely to be conservative.

8. Economics

Hansen et al. [21] offer four reasons to support their conclusion that the trends in annual deployment rates for wind and solar indicate terminal decline to saturation by 2030:

- Long-term decline in PV output caused by solid-state diffusion of dopants within adjacent semi-conducting layers responsible for photon capture and conversion in PV panels;
- Low values for EROEI cited by some authors, in particular for PV;
- The “missing money problem” which refers to the fact that marginal power prices in electricity systems dominated by intermittent sources of energy, such as wind and solar, in the presence of contractual and market mechanisms based primarily on units of electricity generated, tend to zero;

[‡‡] The concept of Energy System Architecture has been defined as “the spatial, topological and functional organisation of energy generation, conversion, transmission, distribution, storage end-use and regulatory systems within the whole energy system” [110].

- High costs of renewables, particularly where cost estimates do not include integration costs.

The first of these can be dealt with using empirical data on the long-term performance of PV which are now available. Reported degradation rates lie in the region of 0.2-0.6% per annum, equivalent to reductions in output of between and 7% and 16% after 30 years of operation [45]. This is insignificant in the light of other sources of uncertainty, not least because the performance statistics of a growing PV fleet will be dominated by the most recently deployed systems. The second reason offered is addressed in Section 5.

With respect to the missing money problem, multiple solutions are available ranging from moving to fully dynamic tariff structures in which capital costs are repaid through high unit costs during periods of scarcity, through hybrid concepts such as contracts-for-difference, to a partial retreat to vertically integrated utilities in which optimal plant mixes are determined by energy system planners off-line [66–68]. Given the range of potential solutions, it is likely that this problem will be overcome, provided the total system cost is low enough – which the analysis presented below suggests will be the case.

The question of additional system costs for wind and PV requires a more extended treatment; in the following section, we examine additional transmission and storage costs through two lenses – investment costs and total expenditure on energy consumption.

8.1 Investment Costs

Learning rates (the fractional reduction in cost per doubling of installed capacity) over the last forty years have been around 20% for solar PV, and 10% for wind [69]. Tables A7-A9 in the Appendix calculate technology cost developments under learning rates of both 10% and 20% for all technologies (with the exception of HVDC transmission, in which no learning is assumed), for each projection. For solar PV, wind technologies and batteries, we derive values for each year (t) using the following formula:

$$Installed\ Cost_t = Installed\ Cost_{t_0}.\left[\frac{Total\ Installed\ Capacity_t}{Total\ Installed\ Capacity_{t_0}}\right]^{(\ln(1-LR)/\ln 2)}$$

where t_0 is 2019 for solar and wind and 2018 for batteries, and LR is the learning rate.

Global weighted-average installed costs for solar and wind for 2019 are sourced from IRENA [70]. For batteries, 2018 installed costs are taken from the estimate provided by NREL [71] for batteries for four-hour storage ($380/kWh), and inflated to 2019 USD ($387/kWh). These values are generally higher than the central estimates for 2019 given by Lazard [72,73]. HVDC cost per MW-mile sourced from the US EIA [74] (as the lower bound estimate, applicable with the economies of scale reached at over 1,200 miles), with the assumed capacity in 2050 (sufficient to transmit 50% of SOLWIN generation) achieved through constant annual capacity additions from 2019.

Installed costs and additional capacity installed in year t are then multiplied to produce total annual investment costs. As with demand for raw materials, we do not calculate costs to replace aging installations for solar and wind, since at the assumed growth rates replacement will be small compared with new capacity. However, we do calculate costs to replace aging batteries, due to their relatively shorter lifespans, and costs for HVDC transmission infrastructure. See Appendix for detailed assumptions, and Tables A10-A12 and A13-A15 for total investment costs in USD and total investment costs as a proportion of projected Gross World Product (GWP), respectively.

We assume annual average GWP growth of 3.5% between 2019 and 2050. GWP thus increases from $87.7 trillion [75] to $255 trillion in real USD 2019. This growth rate is higher than the real-terms CAGR of 2.8% experienced between 1990 and 2019 [76], however we would expect primary energy productivity to continue to increase in the long term (either at or above the 1.2% increase experienced in 2018) [77]. This 2050 value lies between the (inflation-adjusted) projections for SSP3 and SSP4 produced by Dellink et al. [78] – the SSPs with the lowest growth projections - and around two-thirds projected GWP for SSP2, upon which we base our energy demand projections.

In the Central projection, annual SOLWIN investment requirements (including batteries and HVDC transmission) are equivalent to 1.1% and 2.5% GWP in 2050, with learning rates of 20% and 10%, respectively. However, to these projections must be added investment in local transmission infrastructure, which averaged 0.3% GWP in 2010-2019 [79] (and which may be reasonably considered to remain largely constant), and investment in hydrogen production infrastructure. Assuming 21% of final energy consumption in 2050 is satisfied by SOLWIN in in the form of hydrogen initially produced by electrolysis (see Table A5 in the Appendix), with sufficient electrolyser capacity for 2050 deployed at equal rates over 2041-2050, average annual investments would reach around $620 billion, equivalent to 0.24% GWP in 2050 (assuming 74% efficiency and a capital cost of $450/kW as assumed for the long term by the IEA [65], and that electrolysers operate at an average load factor of 50%, in order to contribute to the overall flexibility of the global energy system). Hydrogen storage and distribution costs would require even more modest investment, in part because electrolysers may be placed close to centres of demand (with HVDC capacity transmitting electricity from centres of generation), and much of the existing natural gas infrastructure may be adapted and repurposed for use with hydrogen – this is, for example, a core component of the EU's Hydrogen Strategy [80].

Total investment requirements may therefore reach 1.6-3.0% of GWP in 2050 under the Central projection (but peaking at perhaps 1.9-3.5% GWP in the 2040s). This compares relatively favourably to the rate of 2% GWP-equivalent investment in global energy supply over 2010-2019, and particularly the 2.3-2.4% values experienced in the first half of the decade [79]. Although fossil energy is likely still present in 2050 in this pathway, new investment in fossil fuels would be small.

With investment required for hydrogen supply infrastructure, the total investment requirements for the Low and High projections reach 1.2-2.0% GWP and 1.54-2-74% GWP in 2050, respectively; both lower ranges than the Central projection. Under the Low projection, this is simply due to reduced SOLWIN deployment (and although investment in fossil fuel supply may be higher than in the Central projection, it would likely remain low). In the High projection, unit costs of SOLWIN are lower due to greater cumulative learning, driven by higher levels of investment earlier in the projection.

It is widely accepted that low-carbon energy supply technologies are capital intensive. However, this is typically coupled with low operational costs, as described above. As such, a more instructive metric with which to examine economic constraints to such a transition is the projected annualised cost of supply – expenditure by final energy consumers to recover the costs of capital and operational expenditures over time.

8.2 Expenditure on energy consumption

Evidence suggests that in the long run, expenditure on final energy consumption in OECD countries tends to fall within a range of 8±2% of GDP – the so-called 'Bashmakov-Newbery constant of total energy expenditure' [19]. Within this range, GDP growth is weakly correlated or uncorrelated with energy cost share, but above it, GDP growth declines. For the purposes of the following discussion, and in the absence of opposing evidence, we assume this range applies to the world as a whole.

To determine annualised total costs of energy supply, we first project the levelised cost of energy (LCOE) for solar PV and wind, of storage (LCOS) for batteries, and for HVDC transmission (LCOT). To calculate the LCOE ($/MWh) for capacity installed in year t, the following formula is employed:

$$LCOE_t = \frac{Annualised\ CapEx_t}{Annual\ Generation} + \frac{Annual\ OpEx_t}{Annual\ Generation}$$

where:

$$Annualised\ CapEx_t = Installed\ Cost_t . \left[\frac{(1 - Discount\ Factor)/(1 - Discount\ Factor^{lifetime)})}{\sqrt{Discount\ Factor}}\right]$$

and:

$$Discount\ Factor = \frac{1}{1 + Discount\ Rate}$$

and:

$$Annual\ OpEx_t = Annual\ OpEx_{t_0} . \left[\frac{Installed\ Cost_t}{Installed\ Cost_{t_0}}\right]$$

As the $Discount\ Rate$ we take 7.5%, following the weighted average cost of capital (WACC) assumed by IRENA [70] for the OECD and China (compared to the 10% assumed for the rest of the world). Although we recognise that the cost of capital for renewables varies substantially across countries, technologies and time, with consequent impact on LCOE values [81], we use this single rate for simplicity. WACC values are also likely to decrease and begin to converge over time, as learning continues in the financial sector [82], meaning a global average rate of 7.5% is likely to prove a conservative value toward mid-century[§§].

For $lifetime$ we assume 25 years for all three generating technologies, following IRENA [70]. As illustrated, $Annual\ OpEx$ for new installations is assumed to decrease at the same learning rate employed for installed costs, with values in t_0 (2019) taken as $18.3/kW/year for Solar PV (the OECD value taken from IRENA, taken as an upper estimate of utility-scale installations compared to the non-OECD value of $9.5/kW/year), and $46/kW/year and $76/kW/year for onshore and offshore wind respectively – estimates published by the US EIA in 2017 [83] (and therefore also likely to be upper bound estimates, as supported by the range of estimates provided by IRENA [70]). These estimates reflect the sum of both fixed and variable values, and we assume that such costs do not change over the lifetime of installations, once built.

LCOS for batteries and LCOT for HVDC transmission infrastructure is calculated using the same formula, but with $Annual\ Generation$ (discharge or transmission) determined first by the assumption that 50% of global SOLWIN generation in 2050 would be transmitted and stored by these technologies, and supplemented by the assumptions given in the Appendix. Tables A16-A18 presents the LCOE, LCOS and LCOT values for values in 5-year increments between 2025 and 2050, using both 10% and 20% learning rates (not applicable to HVDC transmission), for each technology, for each trajectory.

To calculate total annualised supply costs for a given technology in year t, we multiply the LCOE, LCOS or LCOT value (as relevant) for year t by new installations in year t, and add to this the results of this same calculation for previous years for installations that have not yet reached the end of their

[§§] We express no opinion on the question of whether current unprecedentedly low interest rates will become a permanent feature of the global economy.

assumed lifetimes. Tables A19-A21 and A22-A24 in the Appendix present total annual supply costs in USD, and as a proportion of projected GWP, for each trajectory, respectively.

Under the Central pathway, consumer expenditure required to recover the investment in electricity generation, storage and HVDC transmission, reaches 2.8-5.5% GWP in 2050. However, to this would be added the cost of local transmission and distribution, hydrogen supply, and the cost of supplying residual energy. For local transmission and distribution, based on the assumption of a consistent annual investment rate equivalent to 0.3% GWP, we consider an annual cost to the consumer equivalent to 0.4% GWP to be a reasonable assumption. For hydrogen, using a high-end estimated production cost of $3/kg for transport (estimates suggest values of $2-3/kg may be reached within 5-10 years under average conditions, and $1-1.5/kg in optimal locations [84]), we estimate the annual cost of supply in 2050 at $4 trillion (1.6% GWP). However, as this includes the price of electricity (generation and transmission), which the IEA estimate would account for around two-thirds the costs of producing hydrogen by electrolysis with renewable electricity in 2030 [65], additional system costs of up to 0.5% GWP is a reasonable approximation.

Under the Central projection, residual primary energy would remain at around one third of total supply by 2050. However, it is reasonable to assume annual energy supply costs would be well below a third of current values, assumed to be around 8% of GWP. This is because production costs of fossil fuels (and derivatives thereof) are likely to decline as demand reduces, they are likely to be delivered by infrastructure that is already amortised, and higher prices would simply encourage an increase in the pace of the transition to SOLWIN. A value of 2.5% GWP is therefore likely to be a reasonable, if not conservative estimation.

As such, under the Central pathway, the total annual costs of energy supply may be 6.2-8.9% GWP in 2050. Using the values given in Tables A23 and A24, and adjusting other supply assumptions given above as appropriate, the total cost of energy supply would be around 6.9-9.2% and 5.0-8.1% for the Low and High trajectories, respectively. These ranges sit entirely within, or below, that of the Bashmakov-Newbery Constant. At the same time, a range of other costs (aside from avoided climate damages) would be reduced or avoided, including the value of subsidies to fossil fuels ($478 billion in 2019 [85], or 0.5% GWP), as would non-climate related externalities associated with fossil fuels (e.g. the economic cost of $PM_{2.5}$ emissions from fossil fuel combustion has been estimated at equivalent to around 3.3% of GWP in 2018) [86].

Although important, discussion of marginal costs on the demand-side of the energy system is beyond the scope of this paper, with the exception of DACCS, which represents a new category of energy demand for which there is no stock of existing infrastructure to replace. Constraints on, and implications of DACCS are dealt with in more detail in the following section.

This shift to a more capital-intensive energy supply system alters the profile and likely sources of investment, but a lack of investors or funds is unlikely to be a concern in the long term. Although the private sector already dominates investment in renewable energy, this is led by project developers themselves, with institutional, private equity and venture capital investors, contributing around 1% in direct investment each [87]. However, as project sizes increase, innovation in investment vehicles and business models continues, and technological familiarity grows, attractiveness to such investors would likely increase further, unlocking more than $100 trillion of assets under management [88]. This is likely to be boosted as investors turn away from increasingly-risky fossil fuel assets (due to short-term volatility, clearly illustrated by the price for WTI oil futures turning negative in early 2020, and the increasing risk of asset stranding in the long-term). In addition, private investment by households and companies in SOLWIN capacity, which accounted for around 25% of renewable investment in 2016 [88], would likely continue.

As with previous energy system transitions, various macroeconomic and geopolitical phenomena are also likely to arise and play a part in defining the shape and pace of a global transition to SOLWIN. These would include the need to restructure economies and labour markets in countries and regions reliant on fossil fuel extraction (e.g. OPEC, and large coal-producing countries from China and India, to Germany and the United States), to be compatible with a low-carbon future. However, the examination of such issues is beyond the scope of this paper.

9. CO_2 emissions and negative-emission technologies

In the vast majority of modelling studies charting pathways to 1.5°C, negative-emission technologies are essential [89]. Until recently there has been an assumption in much of the literature that CO_2 removal would be dominated by bioenergy with carbon capture and sequestration (BECCS). But this technology comes with a range of potential and hard-to-quantify environmental and social consequences [90], and extracts an energy penalty from the system at successive stages of provision (from the biomass supply chain to the energy required to capture CO_2) [91]. For other technologies, such as DACCS, these limitations and indeterminacies are substantially reduced [92–94]. We introduce DACCS, in part in recognition of this, but also because it appears to offer important operational synergies with SOLWIN[***], and appears to ease the problem of managing the final, asymptotic stage of the logistic substitution process.

Projections of potential energy demand for DACCS shown in Figure 1, assume DACCS becomes available at scale in 2040, and is subsequently deployed at a rate of 3 $GtCO_2$ of new capacity a year, up to a maximum annual capture rate of 30 $GtCO_2$, following the limits assumed by Realmonte et al. [92]. Further assumptions used to calculate energy demand for DACCS are described in the Appendix. As with BECCS, DACCS technologies are not yet mature and there is substantial uncertainty surrounding their characteristics and suitability for large-scale deployment. We make no further judgement on the feasibility or realism of such a projection, but present it here to demonstrate the potential effect on cumulative global CO_2 emissions of a rapid, wholesale transformation of energy supply toward SOLWIN in conjunction with CO_2 reduction technology that minimises interaction with the biosphere.

Using a median (constant) costs projection by Realmonte et al. [92] of \$200/tCO_2 captured (see Table A6 in the Appendix for details), the economic cost of such a programme of carbon dioxide removal reaching a rate of capture of 30Gt/year, would be of the order of \$6 trillion by 2050, or 2.4% GWP (inclusive of capital, labour and maintenance costs). The Global CCS Institute estimates CO_2 transport and storage costs for the power sector of \$7-12/tCO_2 [95]. Using a central value of \$10/tCO_2, transporting and storing 30 $GtCO_2$ annually would cost \$300 billion, or 0.1% GWP in 2050.

To project global CO_2 emissions we first calculate the current CO_2 intensity of the global energy system. In 2019, 34 $GtCO_2$ were produced from fuel combustion across 162,194 TWh of TPES [4], producing a CO_2 intensity of 211 tCO_2/GWh. We then assume this CO_2 intensity remains constant for residual TPES. This is likely to be a conservative estimate, as the most CO_2 intensive fuels are likely to be among the first to lose market share - as has happened in the EU, where renewables have tended to displace coal from electricity generation [96]. Other fossil fuels may continue to grow in the short-to-medium term, conversion efficiencies are likely to improve, and in some cases, CCS may be applied directly to mitigate emissions. From 2040, CO_2 emissions captured by DACCS are subtracted from annual CO_2 emissions from the residual TPES to produce a net value. We do not examine the impact on non-CO_2 greenhouse gases, or CO_2 emissions produced outside the energy system.

[***] At times of system stress, it would be possible to shut down DACCS. Provided this were done sparingly, impact on global climate would be small, but the impact on system security could be significant.

Figure 2 illustrates the cumulative CO_2 emissions resulting from the three trajectories. It compares them both with the (CO_2-specific) carbon budgets for 1.5°C and 2°C warming limits [89], and the cumulative CO_2 emissions from the ensemble of 1.5°C scenario pathways underpinning the IPCC's 2018 Special Report [97]. The Appendix provides further detail on assumptions used to produce this chart.

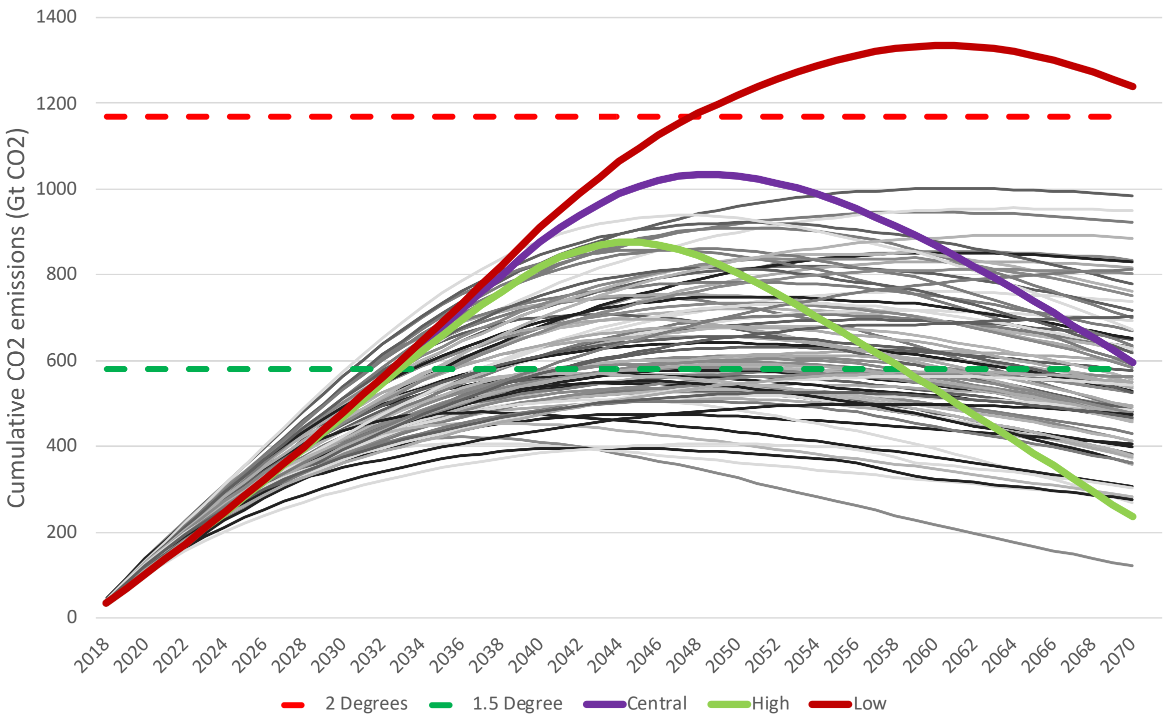

Figure 2 - Cumulative CO_2 emission projections. Note: Grey lines indicate cumulative CO_2 emissions from the ensemble of 1.5℃ scenario pathways underpinning the IPCC's 2018 Special Report [97]

The three projected trends are almost indistinguishable until the late 2030s, after which cumulative emissions peak in 2048 in the Central pathway, and just three years earlier (2045) in the High projection – in both cases below the 2°C carbon budget. Cumulative emissions then decline to below the 1.5°C carbon budget in 2071 and 2058, respectively. Both the Central and High projections fall largely within the emissions trajectories associated with pathways for 1.5°C produced by Integrated Assessment Models (IAMs). The Low projection peaks above the 2°C carbon budget, but then returns to within it shortly after 2070. Assuming no significant change in the oceanic-biospheric CO_2 balance, on our Central projection, cumulative CO_2 emissions over the period from 2018 return to zero by about 2090. By implication, atmospheric CO_2 concentration would also return to 400 ppm at the same date. In the absence of DACCS, atmospheric CO_2 concentration would decline more slowly, with the impacts most obvious in our Central and Low projections.

Although we do not consider non-energy CO_2 emissions, we believe our projections of cumulative CO2 emissions may be reasonably compared with those from modelling studies that do, due our conservative assumptions surrounding the CO_2 intensity of residual energy. We also do not consider the (small) climate forcing feedbacks from SOLWIN deployment discussed above, and outgassing of CO_2 from the oceans, as atmospheric CO_2 is reduced by DACCS (which may offset as much as 19% of the 30Gt/yr sequestered [92]).

Whether investment to achieve such levels of sequestration would be forthcoming, and whether the operational costs could be sustained, would depend on the on-going cost of abatement balanced with estimates of avoided damages and the extent to which they are prices, and is beyond the scope of this paper.

10. Discussion and Conclusions

History contains a number of periods of rapid transformation of the energy system, including the rise of coal during the Industrial Revolution, and its subsequent displacement - first by oil, and then by natural gas - between 1900 and the present. Marchetti & Nakicenovic's analysis established the tendency of technology substitution in energy to follow a logistic model. The feedback between falling costs and increasing demand for the new technology is sufficient to explain both the early approximation to exponential growth of the insurgent technology, and the stagnation and then decline of incumbent technologies, once something like cost parity in key markets has been reached.

We argue that these dynamics are likely to apply to the growth of PV, onshore wind and offshore wind (collectively, 'SOLWIN'), which have demonstrated growth rates over the last 40 years higher than any other energy generation technology for which we have evidence. The question we attempt to address is whether there are fundamental physical and macro-economic barriers to growth that would prevent these technologies continuing to grow such that they achieve dominance in the global energy system by mid-century or shortly after.

Our modelling is deliberately not normative. Its focus is on understanding the implications of growth of SOLWIN at rates broadly consistent with historic trends. Beyond trends that are embedded in a simple extrapolations of global primary energy demand, we have not assumed any increase in end-use efficiency or reduction in energy service demand as a proportion of primary supply. It is possible that ending growth in TPES would make a transition to SOLWIN easier; but the large difference between the growth rates of PV, onshore wind and offshore wind on the one hand, and of global primary energy demand on the other, suggest that the dynamics of the substitution process would be relatively insensitive to the latter. And although some interactions between demand and supply appear likely to speed the process [98], it is not obvious that at the global level, the dynamics of energy demand and supply are simply additive.

We have introduced one additional feature into our projections – DACCS. We show that such a combination of technologies could drive annual global energy-related emissions of CO_2 to, and below, net-zero by the middle of the century. Of our three projections, only our Low projection appears inconsistent with global climate goals. Using conservative assumptions, with the likely exception of the rate of DACCs deployment, we have identified no insuperable physical or macro-economic barrier to such a transition. It therefore appears that a process of substitution is under way which, *if continued*, has the potential to displace fossil fuels from almost all markets between 2050 and 2070. Growth of SOLWIN could, in principle, be curtailed by an as-yet unidentified insurgent energy technology; however such a technology would need to offer even greater advantages for cost effectiveness and emissions mitigation; and would need already to be demonstrating even higher rates of growth. The authors can think of no such candidate.

But, a consequence and a prerequisite for a transition to SOLWIN will be an almost complete reorganisation of the architecture of global and regional energy systems around the new cheaper sources of energy. Such a transformation of energy supply will both require, and drive, a deep reconfiguration of global energy demand toward electricity and derived products, itself dependent on multiple other technological substitution processes across sectors and geographies. Reflection on historical transitions, first from biomass to coal, and then to oil, suggest that such a process would profoundly impact patterns of global trade, and ultimately geopolitics, domains in which human agency is key, but which lie outside the boundaries of our analysis. Failure to achieve such reorganisations would inevitably delay or curtail the substitution process.

Not all technologies that appear promising early in the substitution process go on to dominate the global energy system. In 1979 Marchetti & Nakicenovic commented, it now appears prophetically, on the risks of extrapolating the future of nuclear fission from the roughly 2% of global primary energy it had achieved in 1972 – roughly the level of SOLWIN today. Our work therefore demonstrates the potential for, but not the inevitability of a transition to SOLWIN. We suggest that remaining questions will be decided not by desk studies, but by decisions and action in the real world.

Appendix

Energy, solar and wind growth parameters and assumptions

For the logistic projection of market share in year t, we employ a discrete form of the two-factor logistic equation used by Fisher & Pry [20]. For the case of a single insurgent technology:

$$f_{t+1} = f_t.(1 + \alpha.(1 - f_t))$$

where:

f_t is the fractional penetration of the insurgent technology into the global energy market at time step t.

α is the incremental growth coefficient of the insurgent technology, where $f_t \ll 1$

The simplicity of this discrete form suggests the following extension to the case of multiple insurgent technologies, $x = 1, 2, \ldots$, with associated growth coefficients, α_x:

$$f_{x,t+1} = f_{x,t}.\left(1 + \alpha_x.(1 - \sum_x f_{x,t})\right)$$

The above form is appropriate to a situation in which the insurgent technologies compete separately with the incumbents, but not directly with each other. We consider that this assumption is unlikely to break down until total SOLWIN penetration approaches 100%.

The projections for PV, onshore and offshore wind then require selection of initial values and incremental growth coefficients. In the decade to 2019, the compound annual growth rate for generation from PV, offshore and onshore wind as a proportion of global primary energy consumption was 34%, 25% and 13%, respectively (with annual rates tending to slowly decline and stabilise over this period) [4]. We therefore selected incremental growth coefficients from 2019 of 20% for solar PV and offshore wind, and 10% for onshore wind, as reasonable, but relatively conservative values, for our Central projection. The logistic projection is highly sensitive to changes in the incremental growth coefficient. As such, we present 'High' and 'Low' sensitivities with incremental growth coefficients 5 percentage points higher and lower, respectively, for each technology.

To calculate projected generation for each technology, we multiply projected market share for year t by projected TPES for that year (inclusive of DACCS). To calculate capacity, we divided generation first by annual average capacity factors, and then by the number of hours in the year (8760). For solar PV, we assume the average capacity factor (applicable across all technology vintages) grows linearly from the 2019 value to reach 25% in 2050 (see Table A1). This is consistent with a continued shift of global focus of PV installations to lower latitudes. For onshore and offshore wind, we take the lower quartile value of the projected range for 2030 and 2050 published by IRENA [52] (36% and 42% for 2030, and 39% and 47% for 2050, respectively), with linear interpolations for 2019-2030, and 2030-2050.

Table A1 presents total capacity and generation, and average capacity factor, across all technology vintages, in 2019, and in 5-year increments between 2025 and 2050 , for each projection.

Table A1 - Capacity, generation and capacity factors (2019-2050)

			2019	2025	2030	2035	2040	2045	2050
Solar PV	Low	Capacity (TW)	0.63	1.30	2.50	4.82	9.37	18.95	35.12
		Generation (TWh)	680	1,736	3,764	8,072	17,309	38,255	76,922
	Central	Capacity (TW)	0.63	1.67	3.91	9.00	20.01	42.45	73.02
		Generation (TWh)	680	2,228	5,893	15,091	36,959	85,703	159,907
	High	Capacity (TW)	0.63	2.12	5.96	15.76	36.47	69.17	95.81
		Generation (TWh)	680	2,828	8,894	26,415	67,379	139,627	209,834
	Capacity Factor		12.9%	15.2%	17.2%	19.1%	21.1%	23.0%	25.0%
Onshore Wind	Low	Capacity (TW)	0.59	0.73	0.88	1.20	1.65	2.41	3.32
		Generation (TWh)	1,341	2,000	2,873	3,856	5,413	8,011	11,204
	Central	Capacity (TW)	0.60	0.95	1.44	2.42	4.00	6.64	9.66
		Generation (TWh)	1,341	2,630	4,568	7,795	13,106	22,064	32,573
	High	Capacity (TW)	0.59	1.24	2.29	4.58	8.41	13.88	18.53
		Generation (TWh)	1,341	3,413	7,273	14,761	27,528	46,118	62,480
	Capacity Factor		25.7%	31.5%	36.3%	36.8%	37.4%	37.9%	39%
Offshore Wind	Low	Capacity (TW)	0.03	0.07	0.13	0.27	0.57	1.21	2.36
		Generation (TWh)	86.3	220	478	1,024	2,196	4,854	9,761
	Central	Capacity (TW)	0.03	0.08	0.21	0.51	1.21	2.71	4.90
		Generation (TWh)	86.3	283	748	1915	4,690	10,875	20,291
	High	Capacity (TW)	0.03	0.11	0.31	0.89	2.20	4.41	6.43
		Generation (TWh)	86.3	359	1,139	3,352	8,550	17,718	26,627
	Capacity Factor		34.9%	38.5%	41.5%	42.9%	44.4%	45.8%	47.3%

Land, sea and climate assumptions

For simplicity, we have based our estimates of these impacts on simple exponential projections of PV, and offshore and onshore wind deployments, resulting in installed capacities of 95.8 TW of PV, 10.9 and 7.1 TW in 2050.

The estimation of areas occupied by both technologies is straightforward. The key parameters in the case of solar PV are solar irradiance, conversion efficiency, net-to-gross area ratio and load factor. The primary determinant of load factor at any given site is the distribution of irradiance over the year[†††]. Irradiance and capacity factors are highest around latitude ±23°, and increase with height above sea level. The dominance of Europe and particularly of Germany in global PV deployment between 2000 and 2010 explains why global mean capacity factors during this period were in the region of 10-12%. The shift, in the last decade, in the global focus of PV deployment to lower latitudes has resulted in significantly higher capacity factors, with values approaching 30% for individual projects. We have assumed a global PV fleet mean capacity factor of 25% in 2050. The World Bank's Global Solar Atlas [99] shows large areas of land between latitudes 15° and 30° in both hemispheres with annual mean Global Horizontal Irradiance ≥250 W/m^2, which would support installations with such performance.

Net-to-gross area ratios for large commercial systems are not widely reported. Practicalities, such as the need for access during installation and for maintenance, and to allow panels to be mounted at a tilt, guarantee that this ratio will be less than unity – images of large PV arrays suggest values of 0.5 or above. We have assumed a mean net-to-gross area ratio of 0.5 for the global fleet of PV. With

[†††] Note that PV system designers typically cap the maximum output of arrays in order to reduce the rating of downstream components such as inverters and grid connections. The result is to reduce annual electricity generation but to increase capacity factors.

these assumptions, the gross area occupied by PV systems in 2050 on our High projections would be c.0.96 million km^2, equivalent to 0.6% of global land area.

Estimates of impacts on climate are a little more complex. In the case of PV we have restricted ourselves to examining the first order impact on global radiative flux and climate forcing, caused by the reduction in planetary albedo that results from PV deployment. The albedo of PV panel is reported to be approximately 0.1 [100], while the albedo of sand is approximately 0.4. For systems deployed in regions with annual mean Global Horizontal Irradiance of 250 W/m^2, the approximate reduction in the upward short-wave flux resulting from covering sand with PV would therefore be of the order of 75 W/m^2. This difference is attenuated by absorption and scattering within the atmosphere, by an amount equal, to first order, to the clearness index of the atmosphere, which in tropical regions would be of the order of 65%.

The consequent change in radiative forcing resulting from such an increase in atmospheric CO_2 concentration can be approximated using the following equation [101]:

$$radiative\ forcing\ (t) = 5.35.ln\left[\frac{CO_2(t)}{CO_2(1750)}\right]$$

Averaged over the whole surface area of the planet, the change in radiative forcing from a global PV fleet of c.96 TW$_p$, would be of the order of 0.05 W/m^2. This change can be compared with the additional radiative forcing of c.2.1 W/m^2 that has resulted from the increase in CO_2 concentration from the pre-industrial level of c.280 ppm in 1750 to 415 ppm in 2019. Atmospheric CO_2 concentration is likely to continue to rise to around 500 ppm by mid-century [27,28]), resulting in total radiative forcing of c.3.1 W/m^2 by 2050, more than 60 times larger than the impact of PV at this point.

The 0.05 W/m^2 first order radiative impact of PV is equivalent to the change in forcing that would result from less than 2 years of unconstrained growth in atmospheric CO_2 at mid-century. We conclude that the impact is small in absolute terms, and would be rapidly offset by displacement of fossil energy sources from the global market, and by the deployment of DACCS. We therefore see no need to refine these calculations further.

Analysis is more complex in the case of wind, because of the greater complexity of the thermodynamic/atmospheric processes at work, and the fact that each wind turbine modifies the wind resource available to its neighbours. For wind installations with rated capacities of the order of gigawatts, a first order analysis of areas of land and sea that would be occupied by wind generation is typically based on the concept of limiting power density, a semi-empirical parameter, which, if not exceeded, ensures an acceptable reduction in total generation by interactions between wind turbines. Recent empirical estimates of the limiting power density for offshore wind are of the order of 3 W/m^2 [102,103]. A lower estimate, of 1 W/m^2 for "windy regions" has been proposed by Miller et al. [26] based on regional climate modelling: this lower estimate may be more appropriate to the much larger deployment of wind power envisaged in the present paper. Assuming that this value applies both to onshore and offshore wind power, by 2050 wind farms would need to occupy roughly 12.5% of global land area and roughly 2% of global sea area. Neither of these would appear to present an insuperable problem, although we note that 12.5% of global land area is almost double the land area of the US.

Estimates of climate impacts for wind are also more difficult than for PV. To first order, wind power merely redistributes energy within the global climate system; it has no effect on the net energy flux into that system, and therefore generates no climate forcing. Higher order interactions within the climate system could generate a net global impact, but, in the absence of calculations, we assume that such an impact would be small. However, individually or in arrays, wind turbines create wakes which affect the micro-climate downwind. And it is inevitable that very large wind fleets will affect the climates of the regions across which they are deployed.

It is then appropriate to ask whether such impacts would be manageable, and whether they would be greater or less than the impacts of fossil-based energy systems that wind power displaced. The literature is unfortunately almost silent on these questions - a fully modelled estimate of the climate impacts of very large-scale deployment of wind power using a General Circulation Model (GCM) has, for example, yet to be attempted. But there is some evidence that may begin to help us to understand the possible scale of the regional effects. Miller et al. [26] reported effects on regional climate at all power densities using a regional climate model.

Given the lack of computational capacity, earlier authors used different methods. Adopting a thermodynamic approach, Lorenz [29] was able to estimate the available energy in the global wind system as of the order of 4 PW[‡‡‡]. On this basis, annual wind electricity generation in 2050 at the scale discussed above, would amount to approximately 0.25% of the available energy in the general atmospheric circulation. At this level, impacts on regional climates may be manageable. But it would appear prudent to keep the question of potential adverse climate impacts under review as global wind power capacity increases over the coming decades, and, if necessary, either adjust the regional distribution of the global wind fleet, or reduce the proportion of wind in global energy supply.

Raw material assumptions

Tables A2, A3 and A4 present cumulative metal requirements relative to current reserves and resources to 2050 for the three projections.

[‡‡‡] Strictly, Lorenz estimated the available energy for the Northern Hemisphere as 2 PW. We assume the global value to be twice this.

Table A2 – Metal requirement – Central

Metal	Consumption by 2050 with current rate of production (*and exhaustion year, if pre-2050*)		Solar PV		Wind		Batteries		Total Reserves	Total Resources
	Reserves	Resources	Reserves	Resources	Reserves	Resources	Reserves	Resources		
Aluminium (Al)	27%	11%	2%	1%	0%	0%	12%	5%	41%	16%
Bromine (Br)	43%	0%	0%	0%	0%	0%	-	-	43%	0%
Cadmium (Cd)	103% *(2048)*	13%	690%	84%	0%	0%	-	-	793%	96%
Chromium (Cr)	0%	0%	5%	0%	4%	0%	-	-	9%	0%
Cobalt (Co)	48%	2%	0%	0%	0%	0%	1,213%	59%	1,261%	62%
Copper (Cu)	0%	0%	5%	1%	0%	0%	-	-	5%	1%
Gallium (Ga)	3%	0%	8%	1%	0%	0%	-	-	11%	1%
Gold (Au)	181% *(2036)*	*No data*	5%	*No data*	0%	*No data*	-	-	186%	*No data*
Indium (In)	*No data*	2%	*No data*	32%	*No data*	0%	-	-	*No data*	35%
Iron (Fe)	56%	20%	0%	0%	0%	0%	1%	0%	57%	21%
Lanthanum (La)	22%	*No data*	0%	*No data*	0%	*No data*	-	-	22%	*No data*
Lead (Pb)	166% *(2037)*	7%	9%	0%	0.5%	0%	-	-	175%	8%
Lithium (Li)	8%	3%	0%	0%	0%	0%	658%	199%	666%	201%
Magnesium (Mg)	11%	7%	0%	0%	0%	0%	-	-	11%	7%
Manganese (Mn)	73%	*No data*	1%	*No data*	0%	*No data*	13%	*No data*	86%	*No data*
Molybdenum (Mo)	53%	35%	1%	1%	0%	0%	-	-	54%	36%
Neodymium (Nd)	11%	*No data*	0%	*No data*	1.2%	*No data*	-	-	12%	*No data*
Nickel (Ni)	88%	50%	26%	15%	20%	12%	970%	552%	1,104%	628%
Palladium (Pd)	21%	14%	0%	0%	0%	0%	-	-	21%	14%
Platinum (Pt)	21%	14%	0%	0%	0%	0%	-	-	21%	15%
Rhenium (Re)	64%	15%	0%	0%	0%	0%	-	-	64%	15%
Rhodium (Rh)	21%	14%	0%	0%	0%	0%	-	-	21%	14%
Silver (Ag)	146% *(2040)*	*No data*	21%	*No data*	0%	*No data*	-	-	167%	*No data*
Tantalum (Ta)	13%	*No data*	15%	*No data*	0%	*No data*	-	-	29%	*No data*
Tellurium (Te)	42%	*No data*	4%	*No data*	0%	*No data*	-	-	46%	*No data*
Tin (Sn)	187% *(2035)*	58%	5%	2%	0%	0%	-	-	192%	60%
Titanium (TiO_2)	24%	11%	0%	0%	0%	0%	-	-	24%	11%
Zinc (Zn)	178% *(2035)*	22%	5%	1%	0%	0%	-	-	183%	22%
Zirconium (Zr)	67%	*No data*	1%	*No data*	0%	*No data*	-	-	68%	*No data*

Table A3 – Metal requirement - Low

Metal	Consumption by 2050 with current rate of production (*and exhaustion year, if pre-2050*)		Solar PV		Wind		Batteries		Total Reserves	Total Resources
	Reserves	Resources	Reserves	Resources	Reserves	Resources	Reserves	Resources		
Aluminium (Al)	27%	11%	1%	0%	0%	0%	5%	2%	33%	13%
Bromine (Br)	43%	0%	0%	0%	0%	0%	-	-	43%	0%
Cadmium (Cd)	103% *(2048)*	13%	332%	40%	0%	0%	-	-	435%	53%
Chromium (Cr)	0%	0%	2%	0%	2%	0%	-	-	4%	0%
Cobalt (Co)	48%	2%	0%	0%	0%	0%	545%	27%	593%	29%
Copper (Cu)	0%	0%	2%	0%	0%	0%	-	-	2%	0%
Gallium (Ga)	3%	0%	4%	0%	0%	0%	-	-	7%	1%
Gold (Au)	181% *(2036)*	*No data*	3%	*No data*	0%	*No data*	-	-	183%	*No data*
Indium (In)	*No data*	2%	*No data*	15%	*No data*	0%	-	-	*No data*	18%
Iron (Fe)	56%	20%	0%	0%	0%	0%	0%	0%	57%	20%
Lanthanum (La)	22%	*No data*	0%	*No data*	0%	*No data*	-	-	22%	*No data*
Lead (Pb)	166% *(2037)*	7%	4%	0%	0%	0%	-	-	170%	7%
Lithium (Li)	8%	3%	0%	0%	0%	0%	296%	89%	304%	92%
Magnesium (Mg)	11%	7%	0%	0%	0%	0%	-	-	11%	7%
Manganese (Mn)	73%	*No data*	0%	*No data*	0%	*No data*	6%	*No data*	79%	*No data*
Molybdenum (Mo)	53%	35%	1%	0%	0%	0%	-	-	54%	36%
Neodymium (Nd)	11%	*No data*	0%	*No data*	1%	*No data*	-	-	11%	*No data*
Nickel (Ni)	88%	50%	13%	7%	10%	6%	436%	248%	546%	311%
Palladium (Pd)	21%	14%	0%	0%	0%	0%	-	-	21%	14%
Platinum (Pt)	21%	14%	0%	0%	0%	0%	-	-	21%	14%
Rhenium (Re)	64%	15%	0%	0%	0%	0%	-	-	64%	15%
Rhodium (Rh)	21%	14%	0%	0%	0%	0%	-	-	21%	14%
Silver (Ag)	146% *(2040)*	*No data*	10%	*No data*	0%	*No data*	-	-	156%	*No data*
Tantalum (Ta)	13%	*No data*	7%	*No data*	0%	*No data*	-	-	21%	*No data*
Tellurium (Te)	42%	*No data*	2%	*No data*	0%	*No data*	-	-	44%	*No data*
Tin (Sn)	187% *(2035)*	58%	2%	1%	0%	0%	-	-	190%	59%
Titanium (TiO2)	24%	11%	0%	0%	0%	0%	-	-	24%	11%
Zinc (Zn)	178% *(2035)*	22%	2%	0%	0%	0%	-	-	180%	22%
Zirconium (Zr)	67%	*No data*	0%	*No data*	0%	*No data*	-	-	67%	*No data*

Table A4 – Metal requirement - High

Metal	Consumption by 2050 with current rate of production (*and exhaustion year, if pre-2050*)		Solar PV		Wind		Batteries		Total Reserves	Total Resources
	Reserves	Resources	Reserves	Resources	Reserves	Resources	Reserves	Resources		
Aluminium (Al)	27%	11%	3%	1%	0%	0%	17%	7%	47%	19%
Bromine (Br)	43%	0%	0%	0%	0%	0%	-	-	43%	0%
Cadmium (Cd)	103% *(2048)*	13%	905%	110%	0%	0%	-	-	1,009%	122%
Chromium (Cr)	0%	0%	6%	0%	5%	0%	-	-	12%	1%
Cobalt (Co)	48%	2%	0%	0%	0%	0%	1,711%	84%	1,759%	86%
Copper (Cu)	0%	0%	6%	1%	0%	0%	-	-	6%	1%
Gallium (Ga)	3%	0%	11%	1%	0%	0%	-	-	14%	1%
Gold (Au)	181% *(2036)*	*No data*	7%	*No data*	0%	*No data*	-	-	188%	*No data*
Indium (In)	*No data*	2%	*No data*	42%	*No data*	0%	-	-	*No data*	45%
Iron (Fe)	56%	20%	1%	0%	0%	0%	1%	0%	58%	21%
Lanthanum (La)	22%	*No data*	0%	*No data*	0%	*No data*	-	-	22%	*No data*
Lead (Pb)	166% *(2037)*	7%	12%	1%	1%	0%	-	-	178%	8%
Lithium (Li)	8%	3%	0%	0%	0%	0%	928%	280%	936%	283%
Magnesium (Mg)	11%	7%	0%	0%	0%	0%	-	-	11%	7%
Manganese (Mn)	73%	*No data*	1%	*No data*	0%	*No data*	18%	*No data*	92%	*No data*
Molybdenum (Mo)	53%	35%	2%	1%	0%	0%	-	-	55%	37%
Neodymium (Nd)	11%	*No data*	0%	*No data*	2%	*No data*	-	-	12%	*No data*
Nickel (Ni)	88%	50%	34%	19%	27%	15%	1,368%	779%	1,517%	864%
Palladium (Pd)	21%	14%	0%	0%	0%	0%	-	-	21%	14%
Platinum (Pt)	21%	14%	0%	0%	0%	0%	-	-	21%	15%
Rhenium (Re)	64%	15%	0%	0%	0%	0%	-	-	64%	15%
Rhodium (Rh)	21%	14%	0%	0%	0%	0%	-	-	21%	14%
Silver (Ag)	146% *(2040)*	*No data*	28%	*No data*	0%	*No data*	-	-	174%	*No data*
Tantalum (Ta)	13%	*No data*	20%	*No data*	0%	*No data*	-	-	33%	*No data*
Tellurium (Te)	42%	*No data*	5%	*No data*	0%	*No data*	-	-	47%	*No data*
Tin (Sn)	187% *(2035)*	58%	7%	2%	0%	0%	-	-	194%	60%
Titanium (TiO2)	24%	11%	0%	0%	0%	0%	-	-	24%	11%
Zinc (Zn)	178% *(2035)*	22%	7%	1%	0%	0%	-	-	185%	22%
Zirconium (Zr)	67%	*No data*	1%	*No data*	0%	*No data*	-	-	68%	*No data*

Energy & electricity demand and system integration assumptions

Primary energy substitution & hydrogen

Table A5 presents the calculations and assumptions used to approximate the ratio of substitution between the current fossil fuel based energy supply profile, to SOLWIN.

Table A5 - Primary energy substitution calculations

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	% TFEC	Primary fossil fuels as % of TFEC	Primary SOLWIN (Direct use) as % of TFEC	Primary SOLWIN (via H2) as % of TFEC	Total primary SOLWIN as % of TFEC	Primary energy substitution ratio	Final energy as H2 as % of TFEC
Surface Transport	28%	31%	12%	9%	21%	68%	6%
Aviation	4%	4%	0%	5%	6%	131%	3%
Iron & Steel (Heat)	4%	4%	0%	7%	7%	167%	4%
Iron & Steel (Elec)	1%	2%	1%	0%	1%	55%	-
Cement	3%	3%	0%	5%	5%	167%	3%
Other Industry (Heat)	15%	15%	6%	5%	11%	73%	3%
Other Industry (Elec)	8%	18%	10%	0%	10%	55%	-
Residential (Heat)	17%	17%	6%	3%	9%	54%	2%
Residential (Elec)	5%	11%	6%	0%	6%	55%	-
Commercial (Heat)	8%	8%	3%	1%	4%	54%	1%
Commercial (Elec)	8%	17%	9%	0%	9%	55%	-
Total	**100%**	**131%**	**54%**	**35%**	**90%**	**69%**	**21%**

Column (1) presents the approximate distribution of TFEC between end-use sectors, in 2017 [18]. Column (2) estimates the primary energy consumption associated with each end-use, expressed as a proportion of the TFEC of each sector. In total, 1.31 units of primary energy are (conservatively) estimated to be required for each unit of TFEC, in the current fossil fuel-dominated system. Assuming a constant energy service demand profile, Column (3) estimates the primary energy required (expressed as a proportion of TFEC) from SOLWIN to be used directly as electricity in final end use, taking into account an assumed proportion of each end use that may be electrified, and the relative efficiencies of electricity transmission and forms of energy conversion and delivery this may replace, and the relative efficiencies of end-use technologies (including heat pumps and electric vehicles), and the technologies they replace. Column (4) performs this calculation for the proportion of end-use energy consumption assumed to be satisfied by hydrogen, rather than electricity. Column (5) sums the results of Columns (3) and (4), to illustrate the total primary energy required from SOLWIN to satisfy TFEC through direct electricity and hydrogen as a secondary fuel. Column (6) performs the final step, to estimate how much SOLWIN is required to replace fossil fuel in primary energy supply, for each end-use category, and in total. The results indicate that around 0.69 units of SOLWIN in primary energy is required to replace fossil fuel incumbents, to satisfy the same energy service demand profile.

Finally, Column (7) illustrates the estimated proportion of final energy consumption that may be satisfied by hydrogen, totalling 21%. This is approximately in line with the 18% envisaged by IRENA [104]. Taking into account the primary energy consumption satisfied by SOLWIN in each trajectory and the substitution ratio presented in Column (6), TFEC from hydrogen in 2050 therefore reaches around 161 EJ in the Central projection, and 74 EJ and 226 EJ under the Low and High projections, respectively.

Negative emissions (DACCS)

For consistency, we follow various assumptions provided by Realmonte et al. [92] to parameterise our calculations.

Table A6 - DACCS energy and cost assumptions, reproduced from Realmonte et al. [92] ***Error! Bookmark not defined.***

Technology		Electricity (GJ/tCO_2)	Heat(GJ/tCO_2)	Cost ($/t$CO_2$)
DAC1	High	1.8	8.1	300
	Low	1.3	5.3	180
	Floor	-	-	100
DAC2	High	1.1	7.2	350
	Low	0.6	4.4	200
	Floor	-	-	50

Table A6 reproduces Table 2 in Realmonte et al. [92], upon which we base our energy and cost assumptions. The study produces 'high' and 'low' estimates for electricity and heat energy requirements for two types of DACC technology ('DAC1' reflecting large-scale plants, and 'DAC2', representing modular, mass-produced plants). We adopt median values for electricity (1.2 GJ/tCO_2) and heat (6.25 GJ/tCO_2) requirements across technology types. For heat, we assume 50% is delivered through direct resistance heating (with 100% efficiency), and 50% is delivered through heat pumps, with a coefficient of performance (COP) of 2. This is based on the assumption that DAC2 technologies require heat input (and thus heat pump output) at a temperature in the range 85-120°C [92], which implies a heat pump COP within the range 1.93-2.45, if applied to the following formula:

$$COP = Work\ factor.\left[\frac{Output\ temperature + Heat\ exchanger\ \Delta T + 273}{Output\ temperature - Global\ mean\ temperature + 2.Heat\ exchanger\ \Delta T}\right]$$

where $Work\ factor$ is 0.6, $Heat\ exchanger\ \Delta t$'s are 10°C, $Global\ mean\ temperature$ is 15°C. Essentially, this models heat pumps as devices operating between the global mean temperature and the desired output temperature which are capable of achieving 60% of the performance of the equivalent Carnot engine. This produces a final value of 5.89 GJ/tCO_2 of energy requirement. This value considers energy requirements for direct operation of DACC plants only, and remains constant over time. In practice, waste heat from industrial and electricity generating processes may also be used (*ibid*), and in the case of DAC2, solar thermal, but these options are not explicitly considered here. Cost estimates are discussed under *Economics*, below.

In Figure 2, as the carbon budgets presented are inclusive of CO_2 emissions to 2017, we add emissions for 2018 (34 GtCO_2) [4] to the cumulative projections. Cumulative emissions for the range of modelling scenarios presented are calculated using annual emissions from the five or ten-year time steps provided by the source [97], with annual emissions for intervening years linearly interpolated.

Economics

Installed costs

Tables A7-A9 present projected installed costs in 5-year increments between 2025 and 2050, using both 10% and 20% learning rates, for each technology, for each trajectory.

Table A7 - Projected installed costs - Central

Technology	Learning Rate	2019	2025	2030	2035	2040	2045	2050
2019 USD/kW								
Solar PV	10%	995	850	747	658	583	520	479
	20%		715	544	416	322	252	212
Onshore Wind	10%	1,473	1,371	1,288	1,190	1,102	1,021	964
	20%		1,265	1,109	938	797	678	601
Offshore Wind	10%	3,800	3,220	2,809	2,448	2,147	1,898	1,735
	20%		2,676	2,004	1,497	1,134	874	722
2019 USD/kWh (capacity)								
Batteries	10%	387 *(2018)*	132	105	90	79	70	64
	20%		40	24	18	13	10	8
2019 USD/MW-mile								
HVDC Transmission	-	700	700	700	700	700	700	700

Table A8 - Projected installed costs - Low

Technology	Learning Rate	2019	2025	2030	2035	2040	2045	2050
2019 USD/kW								
Solar PV	10%	995	883	800	724	654	588	535
	20%		775	628	509	411	327	268
Onshore Wind	10%	1,473	1,429	1,389	1,325	1,261	1,191	1,134
	20%		1,382	1,300	1,177	1,060	939	847
Offshore Wind	10%	3,800	3,345	3,007	2,692	2,409	2,146	1,939
	20%		2,900	2,315	1,831	1,448	1,133	914
2019 USD/kWh (capacity)								
Batteries	10%	387 *(2018)*	157	118	102	90	80	72
	20%		57	31	23	18	14	11
2019 USD/MW-mile								
HVDC Transmission	-	*700*	700	700	700	700	700	700

Table A9 - Projected installed costs - High

Technology	Learning Rate	2019	2025	2030	2035	2040	2045	2050
2019 USD/kW								
Solar PV	10%	995	820	701	605	532	483	460
	20%		662	475	347	265	216	194
Onshore Wind	10%	1,473	1,318	1,200	1,080	985	913	873
	20%		1,164	954	764	628	534	487
Offshore Wind	10%	3,800	3,106	2,635	2,248	1,960	1,763	1,665
	20%		2,478	1,751	1,250	935	747	662
2019 USD/kWh (capacity)								
Batteries	10%	387 *(2018)*	120	96	82	71	64	60
	20%		33	20	14	11	9	8
2019 USD/MW-mile								
HVDC Transmission	-	*700*	700	700	700	700	700	700

Annual investment costs

Tables A10-A12 present projected total annual investment costs in 5-year increments between 2025 and 2050, using both 10% and 20% learning rates, for each technology, for each trajectory.

Table A10 - Projected annual investment costs - Central

Technology	Learning Rate	2025	2030	2035	2040	2045	2050
USD 2019 (Trillion)							
Solar PV	10%	0.22	0.46	0.90	1.82	2.82	2.67
	20%	0.19	0.33	0.57	1.00	1.37	1.18
Onshore Wind	10%	0.10	0.15	0.28	0.47	0.60	0.48
	20%	0.09	0.13	0.22	0.34	0.40	0.30
Offshore Wind	10%	0.05	0.09	0.20	0.43	0.70	0.73
	20%	0.04	0.07	0.12	0.23	0.32	0.30
Batteries	10%	0.13	0.24	0.45	1.03	1.64	1.85
	20%	0.04	0.05	0.09	0.17	0.24	0.25
HVDC Transmission	-	0.66					
Total	***10%***	1.16	0.94	1.83	3.75	5.76	5.73
Total	***20%***	1.02	0.58	1.00	1.74	2.33	2.03

Table A11 - Projected annual investment costs – Low

Technology	Learning Rate	2025	2030	2035	2040	2045	2050
USD 2019 (Trillion)							
Solar PV	10%	0.14	0.25	0.43	0.84	1.42	1.87
	20%	0.12	0.19	0.30	0.53	0.79	0.94
Onshore Wind	10%	0.04	0.05	0.10	0.16	0.20	0.18
	20%	0.04	0.04	0.08	0.14	0.16	0.14
Offshore Wind	10%	0.03	0.05	0.10	0.10	0.35	0.50
	20%	0.03	0.04	0.07	0.12	0.19	0.23
Batteries	10%	0.09	0.13	0.21	0.44	0.81	1.16
	20%	0.03	0.03	0.05	0.09	0.14	0.18
HVDC Transmission	-	0.30					
Total	***10%***	0.60	0.48	0.84	1.54	2.78	3.71
Total	***20%***	0.52	0.30	0.50	0.88	1.28	1.49

Table A12 - Projected annual investment costs - High

Technology	Learning Rate	2025	2030	2035	2040	2045	2050
Solar PV	10%	0.33	0.77	1.62	2.97	3.23	1.50
	20%	0.27	0.52	0.93	1.48	1.45	0.63
Onshore Wind	10%	0.19	0.32	0.61	0.98	1.01	0.54
	20%	0.17	0.25	0.43	0.62	0.59	0.30
Offshore Wind	10%	0.07	0.16	0.36	0.70	0.83	0.46
	20%	0.05	0.11	0.20	0.34	0.35	0.19
Batteries	10%	0.19	0.40	0.83	1.67	2.10	1.67
	20%	0.05	0.08	0.15	0.25	0.28	0.21

HVDC Transmission	-	0.92					
Total	***10%***	1.70	1.65	3.42	6.32	7.17	4.17
Total	***20%***	1.46	0.96	1.71	2.69	2.67	1.33

Annual investment costs as a proportion of GWP

Table A13 - Projected annual investment costs (% of GWP) - Central

Technology	Learning Rate	2025	2030	2035	2040	2045	2050
Solar PV	10%	0.2%	0.4%	0.6%	1.0%	1.3%	1.0%
	20%	0.2%	0.3%	0.4%	0.6%	0.6%	0.5%
Onshore Wind	10%	0.1%	0.1%	0.2%	0.3%	0.3%	0.2%
	20%	0.1%	0.1%	0.1%	0.2%	0.2%	0.1%
Offshore Wind	10%	0.0%	0.1%	0.1%	0.2%	0.3%	0.3%
	20%	0.0%	0.1%	0.1%	0.1%	0.2%	0.1%
Batteries	10%	0.1%	0.2%	0.3%	0.6%	0.8%	0.7%
	20%	0.0%	0.0%	0.1%	0.1%	0.1%	0.1%
HVDC Transmission	-	0.6%	0.5%	0.4%	0.4%	0.3%	0.3%
Total	***10%***	***1.0%***	***1.3%***	***1.6%***	***2.5%***	***3.0%***	***2.5%***
Total	***20%***	***0.9%***	***1.0%***	***1.1%***	***1.4%***	***1.4%***	***1.1%***

Table A14 - Projected annual investment costs (% of GWP) – Low

Technology	Learning Rate	2025	2030	2035	2040	2045	2050
Solar PV	10%	0.1%	0.2%	0.3%	0.5%	0.7%	0.7%
	20%	0.1%	0.2%	0.2%	0.3%	0.4%	0.4%
Onshore Wind	10%	0.0%	0.0%	0.1%	0.1%	0.1%	0.1%
	20%	0.0%	0.0%	0.1%	0.1%	0.1%	0.1%
Offshore Wind	10%	0.0%	0.0%	0.1%	0.1%	0.2%	0.2%
	20%	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%
Batteries	10%	0.1%	0.1%	0.1%	0.2%	0.4%	0.5%
	20%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%
HVDC Transmission	-	0.3%	0.2%	0.2%	0.2%	0.1%	0.1%
Total	***10%***	***0.5%***	***0.5%***	***0.8%***	***1.1%***	***1.5%***	***1.6%***
Total	***20%***	***0.4%***	***0.4%***	***0.5%***	***0.7%***	***0.8%***	***0.8%***

Table A15 - Projected annual investment costs (% of GWP) – High

Technology	Learning Rate	2025	2030	2035	2040	2045	2050
Solar PV	10%	0.3%	0.6%	1.1%	1.6%	1.5%	0.6%
	20%	0.2%	0.4%	0.6%	0.8%	0.7%	0.2%
Onshore Wind	10%	0.2%	0.2%	0.4%	0.5%	0.5%	0.2%
	20%	0.2%	0.2%	0.3%	0.3%	0.3%	0.1%
Offshore Wind	10%	0.1%	0.1%	0.2%	0.4%	0.4%	0.2%
	20%	0.0%	0.1%	0.1%	0.2%	0.2%	0.1%
Batteries	10%	0.2%	0.3%	0.5%	0.9%	1.0%	0.7%
	20%	0.0%	0.1%	0.1%	0.1%	0.1%	0.1%
HVDC Transmission	-	0.9%	0.7%	0.6%	0.5%	0.4%	0.4%
Total	***10%***	***1.7%***	***1.9%***	***2.8%***	***3.9%***	***3.8%***	***2.1%***
Total	***20%***	***1.3%***	***1.5%***	***1.7%***	***1.9%***	***1.7%***	***0.9%***

Total annualised cost of supply

Batteries

To calculate battery storage capacity requirements, for simplicity, we assume no seasonality in renewable energy generation, with daily renewable output remaining constant across the year - 50% of which must be stored. We then assume existing storage capacity remains constant to 2050 (4.67 TWh, of 96% of which is pumped hydro) [105], to leave the annual storage capacity requirements that must be satisfied by batteries (reaching 287 TWh, 129 TWh and 405 TWh by 2050 in the Central, Low and High projections, respectively). To determine annual additional storage requirements, we first assume each battery discharges its capacity in full over 12 hours. We calculate the lifetime of each battery by assuming each has the potential for 6,000 charging cycles (an approximate mid-point estimate between 5,475 cycles assumed by NREL [71] for a 4-hour li-ion battery storage installation and 7,000 estimated by Lazard [73]), and each battery is fully charged and discharged one a day, implying a lifetime of 16 years. We assume round-trip efficiency of 90%. This is based on an 85% round-trip efficiency value given by NREL [71] for a 4-hour storage installation, but as batteries are generally more efficient when operating for longer discharge periods, such as the 12-hour discharge period assumed here, we uprated this value. We assume no degradation of battery capacity over time as, following NREL [71], we chose a high value for $Annual\ OpEx$ (2.5% of $investment\ costs$) under the assumption that this will counteract degradation such that the system will be able to perform at rated capacity throughout its lifetime. To translate investment costs in Tables A7-A9 from a kWh to kW basis, we divide by duration of discharge (12 hours), producing a value of $32/kW in 2018. We also exclude from these calculations the cost of the electricity required to charge the battery, to avoid double-counting.

We then sum the capacity of batteries installed within the previous 16 years, and subtract the result from total storage requirements in a given year, to give the storage capacity that must be satisfied through the installation of new batteries. In contrast to generation technologies, and due to their relatively short lifetime, we therefore consider capacity that must be replaced when it reaches the end of its lifetime.

HVDC Transmission

We assume sufficient HVDC capacity will be required to transmit 50% of global SOLWIN generation in 2050 (reaching 106 PWh, 48 PWh and 149 PWh in the Central, Low and High projections, respectively) from 20° latitude to 50° latitude (a straight-line distance of around 2,087 miles). This is based on a starting assumption that a high proportion of solar installations will be in the lower latitudes where solar irradiation is highest, and that the energy generated will be required for use in the higher latitudes. However, we consider these values to be high-end assumptions, as by 2050 over half the global population is likely to reside within the tropics [106] (with much of the rest of the population in latitudes lower than 50°), accounting for much of the world's economic growth (with India, Indonesia, Brazil, Mexico and Nigeria projected to be 5 of the top 10 global economies) by 2050 [107]. In addition, 2.9-7.9% of global energy supply projected to be from offshore wind in 2050 (Low-High), for which some of the best global resources are in higher latitudes [108].

We assume that such capacity will operate at full capacity at 90% of the time on average, with equal annual capacity additions (450GW, 207GW and 632GW in the Central, Low and High projections, respectively) over 2020 to 2050 (with such infrastructure having an average lifetime of 60 years). Although transmission at full capacity for 90% of the time is an optimistic assumption, we do not discount it as a possibility when combined with battery storage, and we consider it to be counteracted by the assumptions given above. We assume energy losses of 3% per 1,000km [109].

We assume such infrastructure is in addition to the maintenance, replacement and incremental expansion of existing transmission and distribution networks.

Table A16 - Projected levelised costs - Central

Technology	Learning Rate	2025	2030	2035	2040	2045	2050
LCOE/LCOS/LCOT (USD 2019/MWh)							
Solar PV	10%	67.25	52.35	41.42	33.28	27.17	23.06
	20%	56.85	38.30	26.30	18.45	13.25	10.62
Onshore Wind	10%	58.73	47.91	43.69	39.77	36.28	33.77
	20%	54.39	41.38	34.47	28.87	24.16	21.10
Offshore Wind	10%	102.23	82.77	69.71	69.16	50.67	44.90
	20%	85.47	59.41	42.89	31.44	23.47	18.80
Batteries	10%	51.39	40.89	35.07	30.70	27.15	24.80
	20%	15.43	9.51	6.87	5.18	4.00	3.30
HVDC Transmission	-	23.75					

Table A17 - Projected levelised costs - Low

Technology	Learning Rate	2025	2030	2035	2040	2045	2050
LCOE/LCOS/LCOT (USD 2019/MWh)							
Solar PV	10%	69.77	55.98	45.50	37.31	30.67	25.74
	20%	61.45	44.13	32.09	23.50	17.14	12.95
Onshore Wind	10%	61.11	51.56	48.43	45.41	42.24	39.64
	20%	59.16	48.34	43.07	38.22	33.35	29.64
Offshore Wind	10%	106.5	88.50	76.57	66.31	57.21	50.12
	20%	92.38	68.45	52.32	40.03	30.34	23.73
Batteries	10%	61.21	45.95	39.65	35.05	31.05	27.99
	20%	22.35	12.18	8.91	6.86	5.31	4.26
HVDC Transmission	-	23.75					

Table A18 - Projected levelised costs - High

Technology	Learning Rate	2025	2030	2035	2040	2045	2050
LCOE/LCOS/LCOT (USD 2019/MWh)							
Solar PV	10%	64.92	49.17	38.08	30.41	25.25	22.15
	20%	52.77	33.53	22.01	15.24	11.35	9.42
Onshore Wind	10%	56.55	44.72	39.63	35.59	32.49	30.64
	20%	50.21	35.76	28.18	22.82	19.13	17.18
Offshore Wind	10%	98.71	77.74	64.10	54.06	47.10	43.13
	20%	79.36	52.02	35.91	25.98	20.11	17.27
Batteries	10%	46.84	37.42	31.76	27.74	24.97	23.53
	20%	12.68	7.88	5.57	4.18	3.35	2.95
HVDC Transmission	-	23.75					

Table A19 - Projected total annual supply costs – Central

Technology	Learning Rate	2025	2030	2035	2040	2045	2050
USD 2019 (Trillion)							
Solar PV	10%	0.10	0.31	0.72	1.51	2.93	4.64
	20%	0.09	0.25	0.53	0.98	1.71	2.45

Onshore Wind	10%	0.07	0.17	0.32	0.54	0.87	1.16
	20%	0.07	0.16	0.28	0.44	0.67	0.84
Offshore Wind	10%	0.02	0.06	0.15	0.32	0.65	1.07
	20%	0.02	0.05	0.10	0.20	0.36	0.54
Batteries	10%	0.04	0.20	0.51	1.17	2.60	4.60
	20%	0.02	0.06	0.12	0.23	0.44	0.70
HVDC Transmission	-	0.51	0.93	1.35	1.77	2.19	2.61
Total	***10%***	0.74	1.67	3.05	5.31	9.24	14.08
Total	***20%***	0.71	1.45	2.38	3.62	5.37	7.14

Table A20 - Projected total annual supply costs – Low

Technology	**Learning Rate**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
USD 2019 (Trillion)							
Solar PV	10%	0.07	0.19	0.40	0.77	1.46	2.45
	20%	0.07	0.17	0.32	0.69	0.96	1.45
Onshore Wind	10%	0.04	0.08	0.13	0.21	0.32	0.41
	20%	0.04	0.08	0.13	0.19	0.28	0.34
Offshore Wind	10%	0.01	0.04	0.08	0.16	0.32	0.57
	20%	0.01	0.03	0.06	0.11	0.20	0.32
Batteries	10%	0.05	0.23	0.58	1.33	2.96	5.25
	20%	0.02	0.07	0.16	0.30	0.57	0.92
HVDC Transmission	-	0.23	0.43	0.62	0.81	1.01	1.20
Total	***10%***	0.40	0.97	1.81	3.28	6.07	9.88
Total	***20%***	0.37	0.78	1.29	2.10	3.02	4.23

Table A21 - Projected total annual supply costs – High

Technology	**Learning Rate**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
USD 2019 (Trillion)							
Solar PV	10%	0.14	0.47	1.19	2.54	4.49	5.99
	20%	0.12	0.36	0.80	1.51	2.42	3.01
Onshore Wind	10%	0.11	0.30	0.61	1.08	1.71	2.11
	20%	0.11	0.26	0.49	0.80	1.18	1.37
Offshore Wind	10%	0.03	0.09	0.24	0.54	0.99	1.36
	20%	0.02	0.07	0.16	0.31	0.51	0.65
Batteries	10%	0.04	0.18	0.46	1.06	2.37	4.24
	20%	0.02	0.07	0.16	0.31	0.51	0.65
HVDC Transmission	-	0.71	1.30	1.89	2.48	3.08	3.67
Total	***10%***	1.03	2.34	4.39	7.70	12.64	17.37
Total	***20%***	0.98	2.06	3.50	5.41	7.70	9.35

Table A22 - Projected annual supply costs (% of GWP) – Central

Technology	**Learning Rate**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Solar PV	10%	0.1%	0.2%	0.5%	0.8%	1.4%	1.8%
	20%	0.1%	0.2%	0.3%	0.5%	0.8%	1.0%
Onshore Wind	10%	0.1%	0.1%	0.2%	0.3%	0.4%	0.5%
	20%	0.1%	0.1%	0.2%	0.2%	0.3%	0.3%
Offshore Wind	10%	0.0%	0.0%	0.1%	0.2%	0.3%	0.4%
	20%	0.0%	0.0%	0.1%	0.1%	0.2%	0.2%
Batteries	10%	0.1%	0.2%	0.3%	0.6%	1.2%	1.8%

	20%	0.0%	0.0%	0.1%	0.1%	0.2%	0.3%
HVDC Transmission	-	0.5%	0.7%	0.9%	1.0%	1.0%	1.0%
Total	***10%***	***0.8%***	***1.2%***	***2.0%***	***2.9%***	***4.3%***	***5.5%***
Total	***20%***	***0.7%***	***1.0%***	***1.6%***	***1.9%***	***2.5%***	***2.8%***

Table A23 - Projected annual supply costs (% of GWP) – Low

Technology	**Learning Rate**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Solar PV	10%	0.1%	0.2%	0.3%	0.4%	0.7%	1.0%
	20%	0.1%	0.1%	0.2%	0.3%	0.4%	0.6%
Onshore Wind	10%	0.0%	0.1%	0.1%	0.1%	0.1%	0.2%
	20%	0.0%	0.1%	0.1%	0.1%	0.1%	0.1%
Offshore Wind	10%	0.0%	0.0%	0.1%	0.1%	0.2%	0.2%
	20%	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%
Batteries	10%	0.0%	0.2%	0.4%	0.7%	1.4%	2.1%
	20%	0.0%	0.1%	0.1%	0.2%	0.3%	0.4%
HVDC Transmission	-	0.2%	0.3%	0.4%	0.5%	0.5%	0.5%
Total	***10%***	***0.3%***	***0.8%***	***1.3%***	***1.8%***	***2.9%***	***4.0%***
Total	***20%***	***0.3%***	***0.6%***	***0.8%***	***1.2%***	***1.4%***	***1.7%***

Table A24 - Projected annual supply costs (% of GWP) – High

Technology	**Learning Rate**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Solar PV	10%	0.1%	0.4%	0.8%	1.4%	2.1%	2.3%
	20%	0.1%	0.3%	0.5%	0.8%	1.1%	1.2%
Onshore Wind	10%	0.1%	0.2%	0.4%	0.6%	0.8%	0.8%
	20%	0.1%	0.2%	0.3%	0.4%	0.6%	0.5%
Offshore Wind	10%	0.0%	0.1%	0.2%	0.3%	0.5%	0.5%
	20%	0.0%	0.1%	0.1%	0.2%	0.2%	0.3%
Batteries	10%	0.0%	0.1%	0.3%	0.6%	1.1%	1.7%
	20%	0.0%	0.0%	0.1%	0.1%	0.2%	0.2%
HVDC Transmission	-	0.7%	1.0%	1.2%	1.4%	1.4%	1.4%
Total	***10%***	***0.9%***	***1.8%***	***2.9%***	***4.3%***	***5.9%***	***6.7%***
Total	***20%***	***0.9%***	***1.6%***	***2.2%***	***2.9%***	***3.5%***	***3.6%***

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